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THESIS

INVESTIGATION OF THE FLIGHT CONTROL
REQUIREMENTS OF A HALF-SCALE DUCTED FAN
UNMANNED AERIAL VEHICLE

by

Mark A. Brynestad

March, 1992

Thesis Advisor: Richard M. Howard

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The following items were accomplished: (1) thrust was improved over the original vehicle through the design and construction of an effective bellmouth and nine-bladed fan; (2) control-vane effectiveness was determined, and stator vanes were designed and installed; (3) gyro stabilization was incorporated into the roll axis controls and the ducted fan flew in a controlled, tethered hover; and (4) gyroscopic cross-coupling was demonstrated.

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Investigation of the Flight Control Requirements of a Half-Scale Ducted Fan Unmannned Aerial Vehicle

by

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ABSTRACT

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I. INTRODUCTION

A. PROBLEM STATEMENT

The Navy needs an Unmanned Aerial Vehicle (UAV) capable of vertical launch from the decks of combatant ships, with a 100 nm range, a dash speed greater than 100 knots and the ability to loiter on station for 3 hours or more. Other services require a vehicle capable of confined area operations with similar range and speed characteristics.

A UAV based on a ducted fan is a potential candidate to meet these requirements. Positioned vertically, a ducted fan could provide enough lift for vertical launch and landing; positioned horizontally, it could provide more efficient thrust than a free propeller. By containing the propeller in a duct, personnel are protected from the fan blades, contributing to safer operations.

Research must determine:

(a) the engine, duct, and fan characteristics necessary to fly this vehicle vertically and horizontally.

(b) an effective method to stabilize and control the vehicle in vertical flight.

(c) the method for repositioning the duct in-flight from the vertical to the horizontal position.

B. THESIS OBJECTIVES

The goal of this thesis was to test and fly the half-scale ducted-fan Unmanned Aerial Vehicle (UAV) designed and built by Ellwood [Ref. 1] and Blanchette [Ref. 2] in horizontal and vertical flight as a proof of concept for a full-scale UAV of similar design.

Consequently, the investigation examined:

1. Methods to increase thrust from the ducted-fan propulsion system.

2. The effectiveness and necessary coupling of the four control vanes in controlling the vehicle in vertical flight (pitch, roll, and yaw) and in countering the engine torque.

3. A stator vane design to counter engine torque with minimum thrust loss.

The results of this thesis should indicate the critical design features of a ducted-fan vehicle. The follow-on project to build a full-scale UAV should benefit from the knowledge and insights gained here, especially in the areas of duct design, propeller characteristics, and vane control.

II. BACKGROUND

A. NAVY UAV APPLICATIONS AND REQUIREMENTS.

Unmanned Aerial Vehicles (UAV) are combat proven remotely piloted aircraft capable of completing missions too risky for manned aircraft or missions where manned aircraft assets are unavailable. UAVs conduct real-time intelligence gathering, Naval Surface Fire Support, target location, identification and mapping, Battle Damage Assessment (BDA) and other naval missions.

Based on experience gained in combat operations in Grenada, Panama, Libya, and Kuwait, the Navy has refined a requirement for UAV reconnaissance missions at sea and inshore areas. Known as VIPER (Vertical Takeoff and Landing, Integrated Platform for Extended Reconnaissance), the naval maritime UAV specifications [Ref. 3] call for a vehicle capable of operating from air capable ships e.g. destroyers, frigates, et al. with embarked LAMPS (Light Airborne Multi-Purpose System) detachments. The VIPER should be able to transit 100 nm from the ship in a 25-knot headwind in less than 1 hour and remain on station for 3 hours. Semi-autonomous launch and recovery is desired within an area smaller than a LAMPS flight deck. The aircraft should carry a minimum 200-pound payload designed to provide real time Reconnaissance, Surveillance and Target Acquisition data

(RSTA) used for Over The Horizon Classification and Targeting (OTH-C&T), Naval Surface Fire Support, Battle Damage Assessment and off board electronic countermeasures (ECM) for Anti-Ship Missile Defense (ASMD). An ideal vehicle should operate efficiently and safely ashore and at sea with minimal support equipment.

This thesis is based on the investigation of the features of a small scale tilting-ducted-fan UAV leading to the design and construction of a full-scale UAV. Although not specifically designed for the VIPER mission, this UAV may determine whether a tilting-ducted-fan aircraft can meet Navy requirements.

B. ARCHYTAS CONCEPT.

Archytas was a Greek scientist, statesman, and colleague of the philosopher Plato who, according to legend, designed, built, and successfully flew a heavier-than-air mechanical bird. His name was adopted for the first UAV concept designed and built at the Naval Postgraduate School. ARCHYTAS is a tilting-ducted-fan (TDF) concept vehicle combining the features of the AQUILA UAV airframe with the ducted-fan propulsion and control system of another UAV, the Airborne Remotely Operated Device (AROD). Conceptually, the ducted fan is positioned vertically in the airframe for vertical flight, and tilted forward to propel the aircraft in horizontal flight.

A small-scale flying vehicle of this type was built to gain information and experience on the viability of this concept. This scaled-down ARCHYTAS is a technology demonstrator aircraft using off-the-shelf radio controlled (RC) model components built by Ellwood [Ref. 1] and Blanchette [Ref. 2]. The airframe is a half-scale model of the AQUILA and the ducted-fan/vane control unit is roughly a half-scale model of the AROD. The merging of two vehicle types into the ARCHYTAS was done to eliminate the weaknesses and to capitalize on the strengths of each vehicle.

The UAV concept that became the AQUILA [Ref. 4, pp 167-169] was originally conceived in 1974, built by Lockheed Missiles and Space Co., and first successfully demonstrated its operational capability in 1986. It had good range, payload and endurance characteristics (Table 1), with a low radar cross section and simple construction, but it suffered from poor lateral-directional and longitudinal stability characteristics in certain flight regimes.

The AROD was a short-range optically or radio-controlled hovering ducted-fan UAV developed by Sandia National Laboratories. It first flew in 1986, weighed about 85 pounds, and had an endurance of about a hour. Four vanes positioned in the fan wake were used to maneuver the aircraft. Its forward speed and endurance were limited due to its hover mode of translation, but it operated easily from confined areas and

was safe to operate since personnel were not exposed to the fan blades.

Table 1. AQUILA CHARACTERISTICS [REF. 4].

Wing span	12 ft 8.75 in
Length overall	6 ft 10 in
Propeller diameter	2 ft 2 in
Engine characteristics	24 hp, 8000 rpm
Maximum payload	114.5 lbs
Maximum fuel weight	89 lbs
Maximum launching weight	331 lbs
Dash speed	113 kts
Cruising speed	73 - 94 kts
Loiter speed	70 kts
Service ceiling	14,765 ft
Endurance	10 hrs

The half-scale ARCHYTAS uses the same airfoil and wing/fuselage planform of the AQUILA with the addition of a twinboom tail. The boom length of the tail is adjustable to allow testing of the stability characteristics of different rudder/elevator locations. An AROD-shaped ducted fan is incorporated into the fuselage center sectic of the half-scale ARCHYTAS near the center of gravity. This ducted fan can be installed either vertically for hover, takeoff, and

landing flight regimes or horizontally for typical airplane flight, but does not have the tilting mechanism to transition from one regime to the other. Space and weight allow for future installation of a telemetry package.

In the technology demonstrator program, information gained from flying the half-scale ARCHYTAS will be used to modify a full-scale AQUILA to the tilting-ducted-fan ARCHYTAS configuration.

Advantages of the TDF design include:

a. Safety. The duct protects personnel from entanglement in the fan blades and protects the fan blades should the vehicle overturn.

b. Versatility. The vehicle can be operated from confined spaces using the vertical takeoff capability. Once airborne, clear of all obstacles, the ducted fan would be tilted forward in flight to the horizontal flight position for high speed transit or efficient loiter, or the vehicle may be operated from short runways ashore in the conventional horizontal takeoff and landing configuration.

c. Efficiency. The ducted fan is more efficient in the desired operating speed range than a propeller or a helicopter type vehicle. The TDF will have a higher dash speed and greater endurance than a helicopter, and be more efficient in the desired cruise speed range than a propeller-driven vehicle.

d. Compactness. A ducted fan produces the same thrust with a smaller fan diameter than a free propeller/rotor, resulting in a more compact vehicle.

The advantages of a ducted fan demand serious consideration for use in future vehicles carrying out the varied naval missions of the future. Personnel safety and operating efficiency will be the hallmarks of the successful maritime UAV.

III. HALF-SCALE ARCHYTAS DESIGN

A. ORIGINAL DESIGN.

Ellwood [Ref. 1] and Blanchette [Ref. 2] built the original half-scale ARCHYTAS using techniques common to radio-control modelers. The fuselage is composed of fiberglass over a balsa, plywood, and foam frame. An I-beam main spar of fiberglass over balsa wood provided the strength; fiberglassed blue foam provided the airfoil shape of the wings. Aluminum tubing with fiberglass covering foam tail surfaces made up the twin boom T-tail section. Propulsion came from a single-cylinder, two-cycle glow-fueled engine driving a three-bladed propeller in a ducted fan. A standard radio-controlled model aircraft 8-channel receiver and servos drove conventional ailerons, flaps, rudders, elevator, and engine throttle control. Nosewheel steering was incorporated through the rudder channel. The aircraft taxied successfully in this configuration, but never flew because the nose would not rotate off the ground with full elevator deflection due to perceived center of gravity and landing gear location problems.

B. DESIGN ENHANCEMENTS.

The following paragraphs discuss several engineering modifications to the basic design performed to improve performance.

1. Wingtips.

a. ***Original Design.*** The original ARCHYTAS wingtips were square and of no unusual shape.

b. ***Reason for Change.*** The wings were made of foam and covered with a light grade fiberglass cloth susceptible to damage should a wingtip inadvertently contact the ground.

c. ***Solution.*** Winglets were added to the wingtips for protection and to improve wing efficiency.

d. ***Construction/Incorporation.*** The winglets were shaped of blue foam, covered by fiberglass and bolted to the original wingtips. Plywood formed the lower edge of the winglets and protected the winglet from damage from ground contact.

e. ***Results.*** The left wingtip inadvertently contacted the ground on one occasion at flying speed and suffered no damage.

f. ***Limitations.*** The only disadvantage of having winglets is the added weight, approximately one-half pound total. However, compared to the potential time savings to

repair any damage, the weight penalty was considered acceptable.

2. Landing Gear.

a. Original Design. The original landing gear consisted of an aluminum fuselage mount, gear shaft, and wheel fork, and a steel axle with model-aircraft shock absorbers and tires [Ref. 1 pp. 38].

b. Reason for Change. With the original main landing gear, approximately one pound of lead ballast in the nose was required to keep the center-of-gravity near 25% MAC. Due to an error in the initial construction, the nose gear supported nearly 21% of the gross weight and the aircraft could not rotate to takeoff.

c. Solution. A new landing gear configuration was designed to relocate the wheel axles forward of the original wheel mounting locations. The main gear legs were constructed of fiberglass to reduce weight, provide a wider wheelbase, and move the wheels forward.

d. Construction/Incorporation. The new main landing gear, using 15 layers of eight-ounce fiberglass cloth and epoxy resin, was formed over an inverted "U" shaped jig. After installation the new main mounts were heated and manually twisted to align the wheels with the aircraft centerline for a straight taxi and landing/takeoff roll. The

new nose gear [App. A] was constructed of material similar to the original. Figure 3.2.1 shows the new landing gear configuration.

e. *Results*. The change moved the center of gravity aft relative to the wheel positions, putting less weight on the nose gear. The new landing gear configuration reduced the lead ballast requirement in the nose to 0.6 pounds and reduced the weight percentage on the nose wheel to about 12 %. The aircraft rotated for takeoff satisfactorily in this configuration on 21 September 1991.

Figure 3.2.1 Landing Gear Configuration

3. **Bellmouth.**

a.Original Design. The original duct had no bellmouth; the leading edge radius was one-eighth inch.

b. Reason for Change. There was no measurable thrust increase from a propeller in the original duct over the thrust of the same propeller unducted. The literature of ducted fans describes the advantages of a properly shaped inlet. To increase the thrust, the duct intake design needed improvement.

c. Solution. Wallis [Ref 5, Chap 4] indicated that inlet losses could be reduced to nearly zero with a thrust increase up to approximately 30% by using a proper inlet shape. To be effective in a crosswind, a bellmouth leading edge radius should increase from leading edge to the duct interior. The minimum radius for a no-crosswind bellmouth was 15% of the duct diameter. The ARCHYTAS duct diameter was 11.5 inches which implied a minimum 1.725-inch radius was necessary.

d. Construction/Incorporation. Since two-inch-thick brown foam sections were readily available, the new bellmouth shape was hand formed from two of these sections. Once the proper shape was attained the new bellmouth was affixed to the duct and covered with 3-ounce fiberglass cloth and epoxy resin.

The interior bellmouth contour was patterned after the shape of the r = 2.6 sin 2θ (A to B in Figure 3.3.1) curve which meets the criteria for a decreasing radius of curvature into the duct. The curve starts tangent to the duct inner surface and projects two inches forward of the previous leading edge. Figure 3.3.2. shows the general layout of the duct. In the upper right corner of Figure 3.3.2 is the bellmouth shape cross section where A to B and the dotted line is the first quadrant of the r = 2.6 sin 2θ curve. A curve tangent to the outer edge of the r = 2.6 sin 2θ curve ending two inches down from the original duct lip completes the exterior surface of the duct.

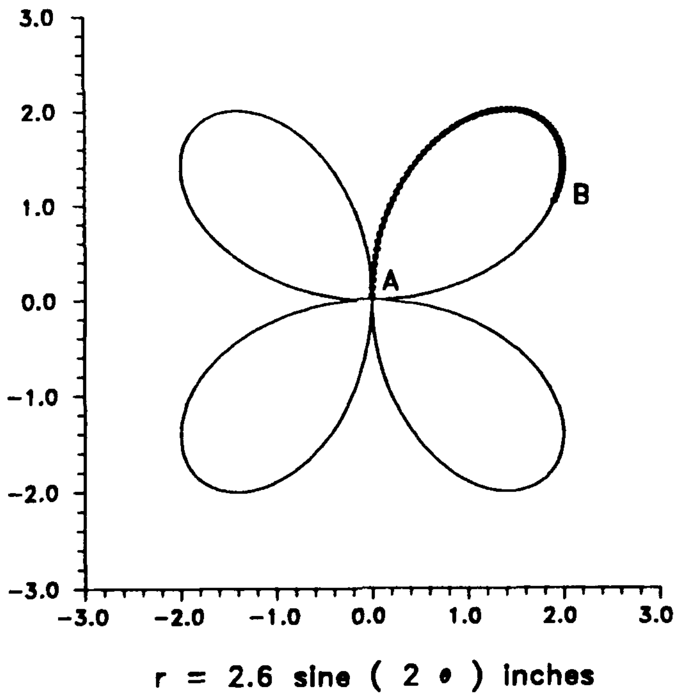

Figure 3.3.1 Bellmouth Shape from A to B.

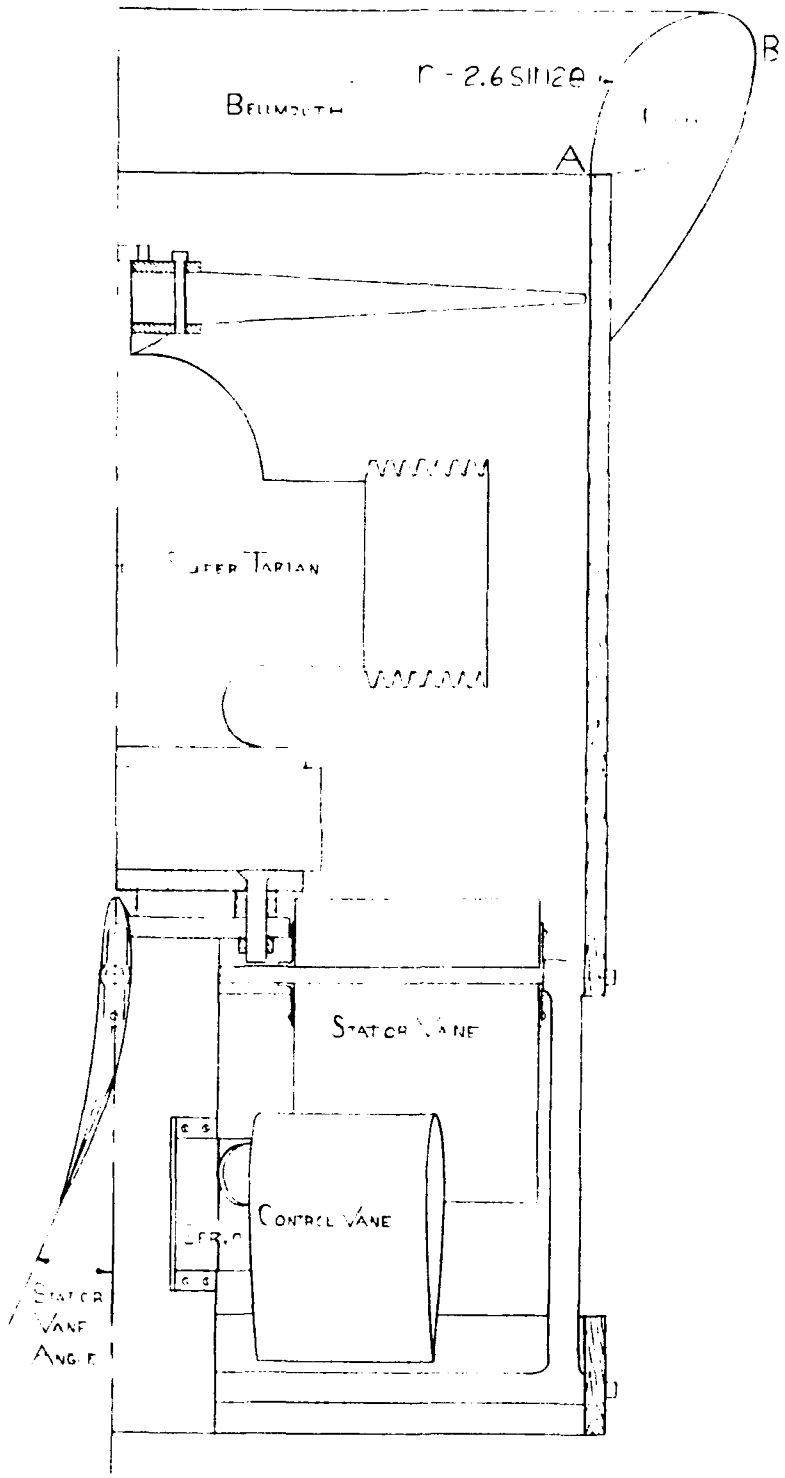

Figure 3.3.2 Duct Interior Configuration.

Removable cutouts in the leading edge were made to allow horizontal installation of the new "propulsion unit", since the new bellmouth diameter was larger than the space provided in the fuselage center section. For vertical flight, the cutouts were reinstalled and taped in place. The fuselage center section was built up to match the bellmouth shape and provide a close fit between the installed duct bellmouth and the fuselage to improve the inlet flow in this area.

e. *Results*. Table 3.1 shows the thrust improvements realized by adding the bellmouth to the duct design. Thrust from the OS-108 engine increased 32 per cent and increased 7.2 per cent for the SUPER TARTAN engine. A reason for the small thrust improvement of the SUPER TARTAN engine may be that it blocks approximately 35 per cent of the duct cross sectional area while the smaller OS-108 engine blocks 23 per cent.

Torque measurements were also taken to compare the effect of engine torque on the airframe due to the duct. Figure 3.3.3 plots Moment (ft-lbs) vs. Engine RPM and shows how the duct with control vanes installed, significantly reduced the moment felt by the airframe. Figure 3.3.3 was completed before any stator vanes were incorporated into the design.

Table 3.1 EFFECTS OF DUCTED BELLMOUTH.

Engine	RPM	Thrust (lbs)	Prop/Duct
OS-108	10060	7	3 blades unducted and ducted w/o bellmouth
OS-108	10220	9.25	3 bladed fan ducted with bellmouth
Super Tartan	7867	13.25	9 bladed fan unducted
Super Tartan	8067	14.25	9 bladed fan ducted with bellmouth

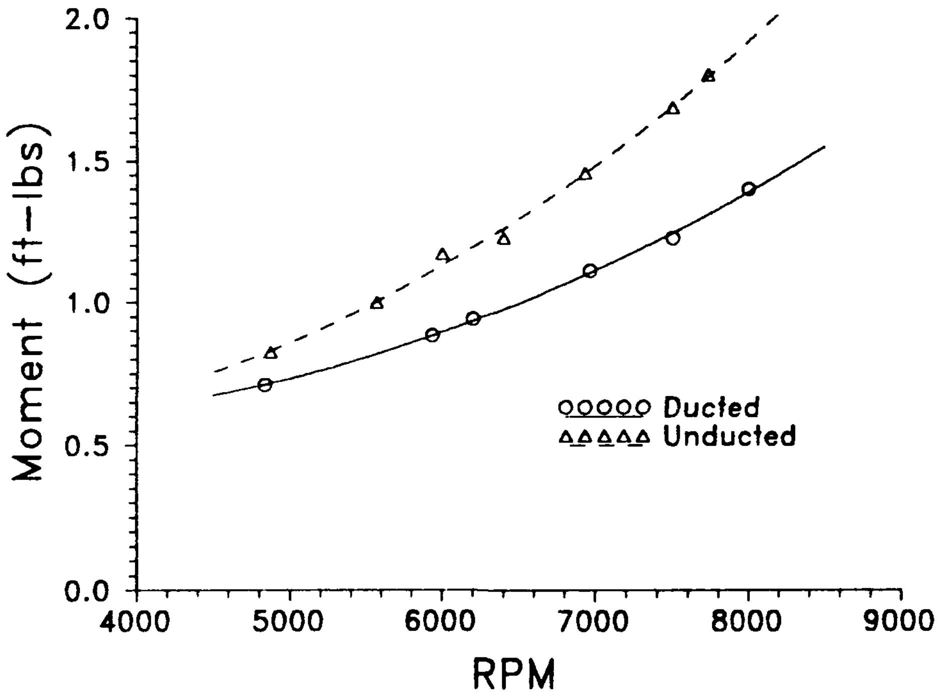

Figure 3.3.3 Moment (ft-lbs) vs. RPM (Super Tartan Engine)

The area around the bellmouth and center section was tufted and filmed to visualize the flow in this area. The tufts indicated smooth flow over the inlet shape into the duct

with some vortices forming where the fuselage crossed in front of the intake.

An additional benefit of the new bellmouth was a noticeable reduction in flow noise. Although no measurements were taken to compare the noise levels before and after, the engine noise was noticeably less after the bellmouth was installed. The literature also predicts this reduction.

f. Limitations. The bellmouth obviously had a weight penalty, but the thrust increase due to the bellmouth far outweighed any increase in vehicle weight.

The major decision in bellmouth design was the design point. The ARCHYTAS bellmouth design point was the low-speed/hover condition, as it must be for the difficult vertical flight regime. The air, accelerating over the opening surface, produces forces in the axial direction. This effect reduces with increasing forward speed. However, by optimizing for vertical flight, the low-speed bellmouth becomes a liability at higher speeds due to higher drag.

4. Propeller.

a. Original Design. In the attempt to generate enough thrust to lift the ARCHYTAS vertically, several propellers were mated with the SUPER TARTAN engine (rated at 3.95 HP at 8800 RPM) and tested for thrust. Ready-made two-bladed propellers that fit the duct diameter oversped the

engine and produced minimal thrust. Propellers with greater diameter, chord, and pitch were shortened to fit the duct, tested and produced five to six lbs. thrust at approximately 10,000 RPM. Reference 2, pp. 74 - 77, lists the results of engine testing with propellers of different size and pitch. None of the propellers provided enough thrust to lift ARCHYTAS vertically with the selected engine.

b. Solution. Obviously only a multi-bladed design could absorb the engine power and potentially provide the desired static thrust. The Graupner (Super Extra) three-bladed 15/8 (15-inch diameter, 8-inch pitch) propeller was the only commercially-produced multi-bladed propeller found. A propeller of this type was shortened to 11 inches to fit the duct interior. With this propeller the SUPER TARTAN engine ran at 10,000 RPM and produced 6.5 lbs. thrust. This RPM was still considerably over the rated RPM of the engine, so a multi-bladed fan was designed and built to absorb the engine power and run at the rated 8800 RPM.

d. Construction/Incorporation. The methods of Hovey [Ref. 6, pp.40] were used to design a multi-bladed fan. An odd number of blades was an initial criterion "to reduce the chance of blade elastic frequencies becoming tuned to shaft resonance harmonic frequencies." The fan was constructed from readily available radio-controlled model propellers to reduce

cost and ensure similarity of the blade shapes. The blade chosen was a Zinger 14/10 (cut to 11.5 inches diameter) because it had a high pitch (10 inches) and it retained the widest part of the chord after the diameter was shortened to fit the duct. Equation 25 of Reference 6 indicated a 9-pitch blade was optimum, so a 10-pitch blade was selected since it was commercially available. Table 3.4.1 lists the initial assumptions made for the Hovey method.

Table 3.4.1. INITIAL ASSUMPTIONS.

Aircraft Weight	25
Duct Diameter	11 in.
Engine RPM	8800 RPM
Blade Chord	1.125 in.
Blade Radius	5.5 in.

From Reference 6, (pp. 40-41), the required number of blades N_b was determined.

$$N_b = A_b / B_a$$

Where A_b = Total area of all blades, square feet.

B_a = radius x chord = area per blade (1.125 x 5.5/144).

$$A_b = (2,000,000) * \frac{T}{D^2 * RPM^2}$$

T = Desired Thrust (25 lbs. = estimated aircraft weight)

D = Diameter at blade tip (11/12 ft)

RPM = Fan speed, revolutions per minute (8800 from engine literature)

Due to the large thrust requirement for the diameter and RPM, the solution implied 18 blades were needed to lift the aircraft vertically, an impossible number. Theoretically a nine-bladed fan would lift 12 pounds (the estimated duct weight), so a fan was designed and built to fly just the duct vertically using a nine-bladed fan.

e. *Results*. Reference 7, pages 26-27, described the construction of an eight-bladed fan from four two-bladed propellers for a ducted-fan model MIG-17. Using the same technique and five Zinger 14/10 propellers, the technical staff at NPS built a nine-bladed fan [Fig. 3.4.1 and App.B].

Figure 3.4.2 shows the variation of thrust with RPM in both the ducted and unducted configurations. Unducted, at full throttle, this engine/propeller combination produced 12.25 pounds of thrust at 7867 RPM. In the duct, at full throttle, 13.25 pounds of thrust were obtained at 8067 RPM. In the duct, the engine produced more RPM and thrust for the same throttle setting.

The duct reduced tip losses (due to the small gap between the duct wall and propeller tip) and altered the input streamlines to the propeller. Reduced tip losses and improved

inflow allowed the engine to turn at a higher RPM and produce more thrust at full throttle.

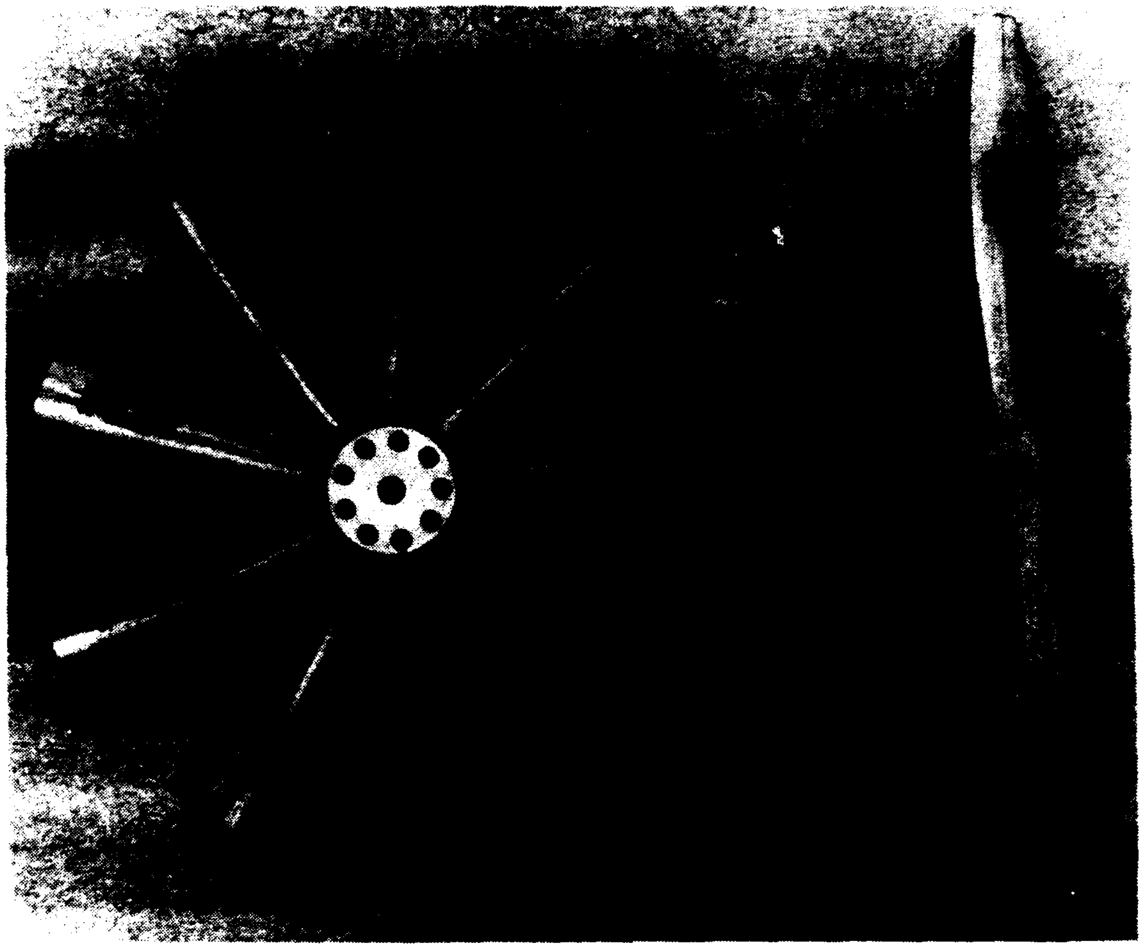

Figure 3.4.1 Nine-Bladed Fan and Two-Bladed Propeller.

Additional engine tests were performed to quantify and compare the actual engine power, torque, and thrust of the ducted fan to the unducted fan, and the results are discussed in the following section.

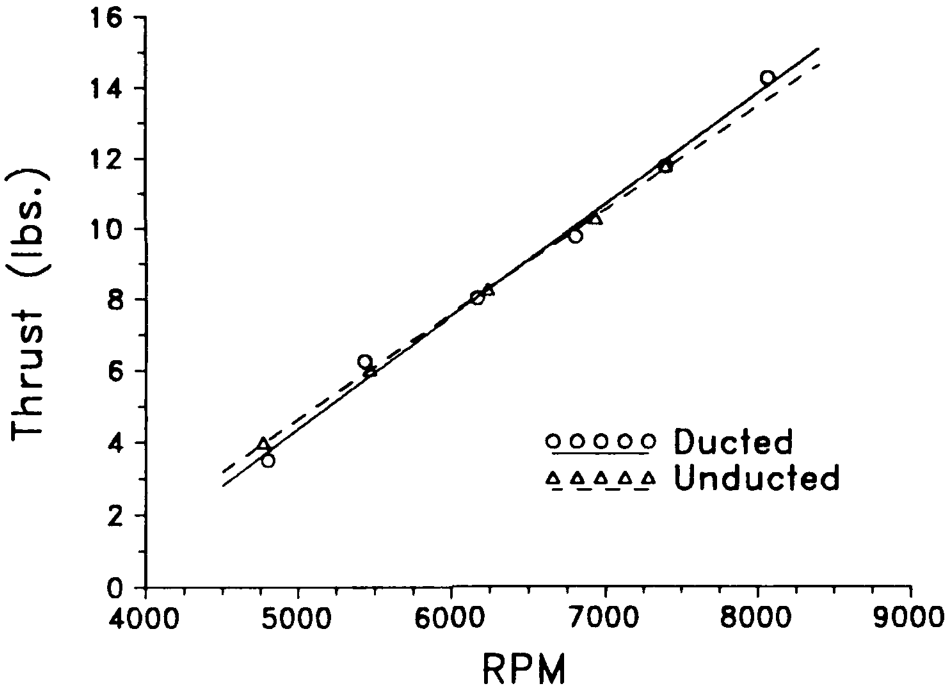

Figure 3.4.2 Thrust vs. RPM (Super Tartan Engine)

f. Limitations. The nine-bladed fan was a preliminary effort to compare the results of a fan design to those of the two-bladed propeller designs. It was easy and inexpensive to construct and test but since it was not specifically designed and optimized for the SUPER TARTAN engine, the efficiency was low, at 42%. The fan efficiency has a large effect on the power required to lift a 30 pound vehicle. Using Hovey's analysis methods, a fan efficiency of 90% would produce 30 pounds of thrust, enough to lift ARCHYTAS vertically with the SUPER TARTAN engine. A computer code

written for ducted fans will be used to design an improved future fan or propeller [Refs. 8 and 9].

5. Engine Characterization.

a. Original Design. As completed by Ellwood and Blanchette, the half-scale ARCHYTAS used an OS-108, single-cylinder, 1.08-cubic-inch, two-cycle glow engine for propulsion. It produced approximately 1.25 Hp and operated at 10000 to 12000 RPM, depending on the propeller.

b. Reason for Change. The OS-108 engine and Graupner three-bladed prop only produced 9.25 pounds of thrust in the duct with the bellmouth. This engine/prop combination was sufficient to fly ARCHYTAS horizontally, but a more powerful engine was required to fly vertically.

c. Solution. The engine selected was a SUPER TARTAN two-cylinder gasoline engine capable of 3.95 horsepower at 8800 RPM [manufacturer's data]. This engine was chosen for its high horsepower rating and anticipated reduced levels of vibration.

d. Construction/Incorporation. A new engine mount was designed to install the SUPER TARTAN engine in the duct. The fuel lines were changed to allow for the use of unleaded gasoline instead of the glow fuel used by the OS-108.

e. Results. To test the thrust provided by different engine/propeller combinations, a thrust stand [Fig.

3.5.1] was used. It consisted of an engine mounting bracket affixed to a sliding tray on a box bolted to a table. A length of welding rod connected the sliding tray to a spring scale. The spring scale measured from zero to 25 pounds in half-pound increments.

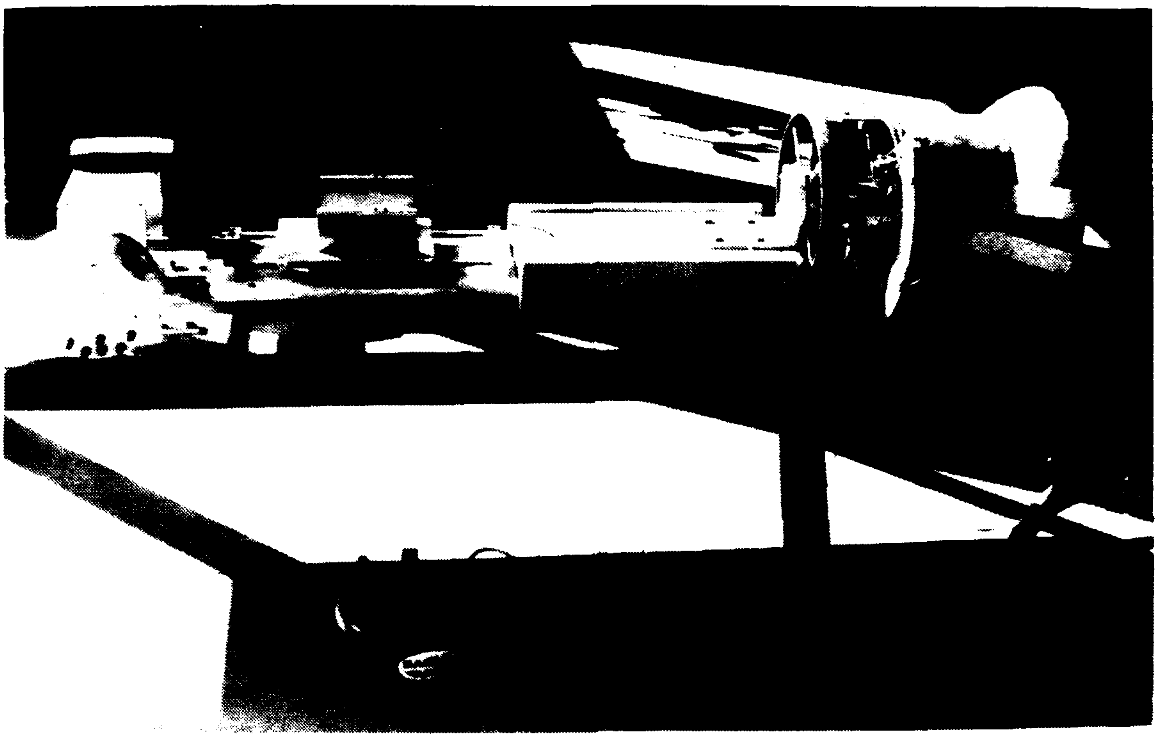

Figure 3.5.1 Engine Thrust Stand.

A small engine torque stand designed and built at NPS was used to obtain torque measurements. The engine mounted to a large one-inch thick disk, the center of which was bolted to a shaft. The shaft was held in place by two bearings allowing rotation but not axial movement. A 22-inch-long, one-by-two inch arm was bolted tangentially to the disk

to provide a moment arm. A spring scale at the end of the 22-inch arm measured a force which was later converted to a torque.

The engine was run at maximum RPM with various propellers to obtain an engine performance curve [Fig. 3.5.2], useful for the future design of an optimized fan for the Super Tartan engine. Figure 3.5.3 shows the engine torque stand.

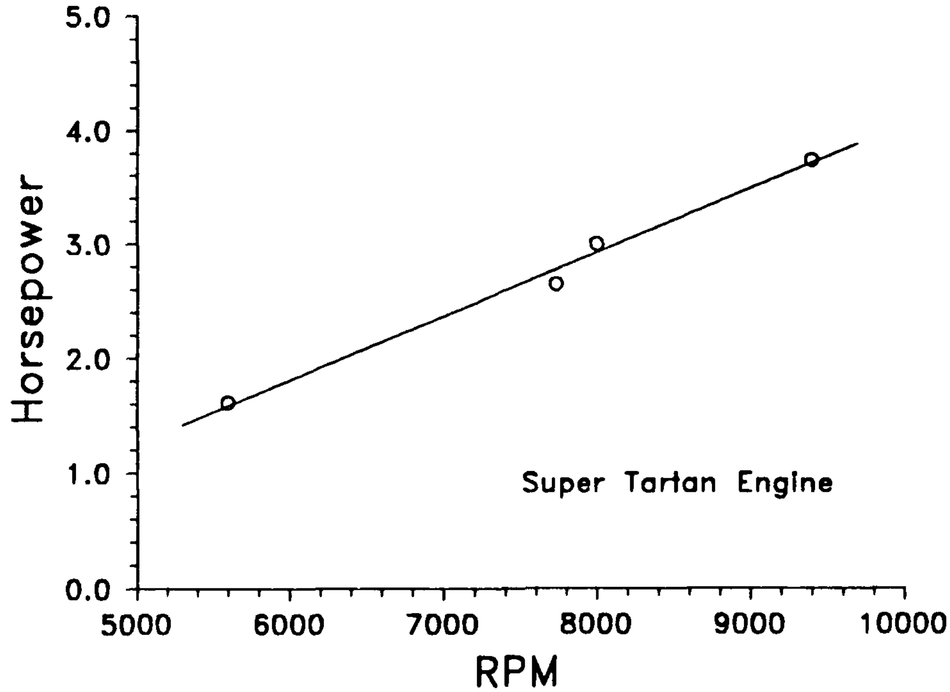

Figure 3.5.2 Horsepower vs. RPM (Super Tartan Engine).

A photocell in the Futaba radio transmitter detected the passing of each fan blade and knowing the number of propeller blades (two through five), the transmitter computed engine RPM. For the nine-bladed fan, RPM was calculated using the three-bladed setting and dividing the indicated RPM by three.

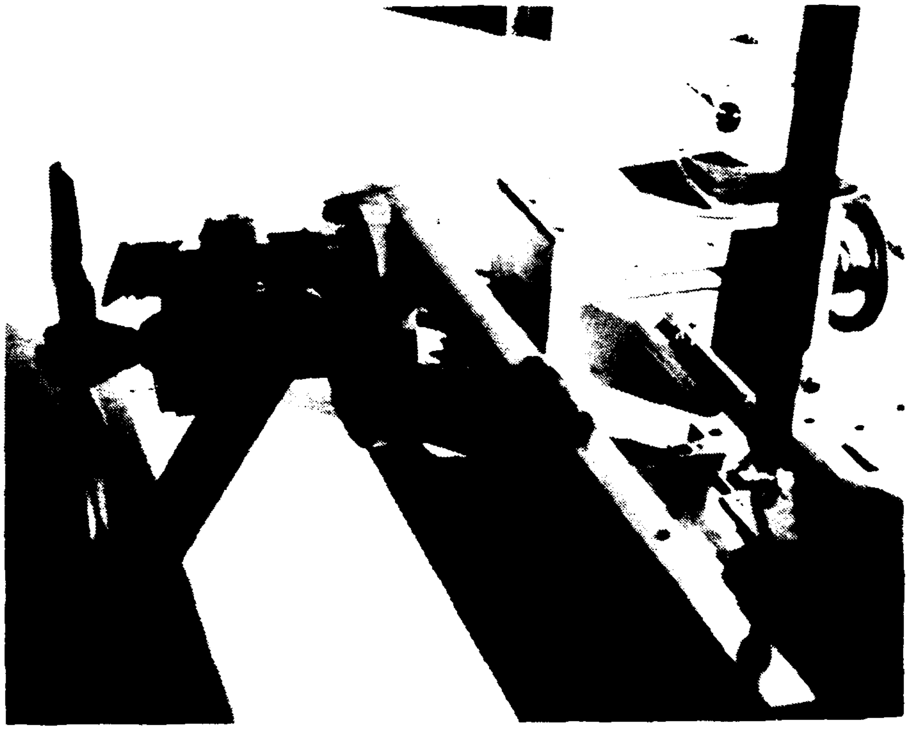

Figure 3.5.3 Engine Torque Stand.

Power available from the Super Tartan engine was plotted in Figure 3.5.2. This engine was run with four different propellers to give different loads to the engine. The plot indicates that the engine produced about 3 Hp at 8000 RPM and never reached the 3.95 HP at 8800 RPM advertised by the manufacturer.

f. Limitations. In the 11.5-inch diameter duct, an engine speed of 8800 RPM produced a tipspeed of only 441 feet per second, well below the 600 to 900 fps tipspeed recommended by Hovey [Ref. 6 pp. 2]. Hovey suggests that below 600 fps

the blade chord must be very wide to obtain the desired thrust, adversely affecting vehicle weight. Above 900 fps the stresses on the propeller blades are too great to safely operate. Figure 3.5.4 plots tipspeed against RPM for a duct diameter of 11.5 inches. This plot indicates the half-scale ARCHYTAS duct size requires an engine capable of at least 12,000 RPM to obtain the minimum recommended tipspeed. Depending on the fan efficiency, the proper engine needs to provide six to nine horsepower. A small engine of this type is not in use by RC modelers and would be expensive to purchase if specially made.

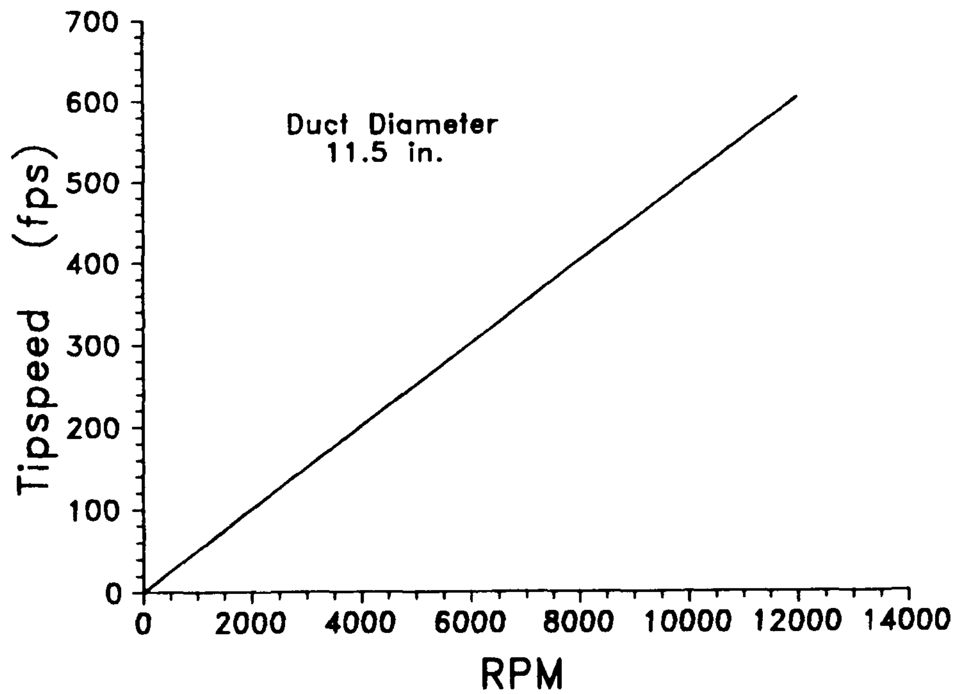

Figure 3.5.4. Tipspeed vs. RPM

The gasoline-fueled SUPER TARTAN engine had limitations associated with it. The gasoline engine required a 24-volt battery and a large starting unit to conduct routine engine testing and the starting unit could not be adapted to start the engine in the horizontal duct configuration.

The 92 octane unleaded gasoline has less energy than glow fuel and is incompatible with the glow fuel lines and fuel tank plugs. Converting the aircraft from the glow fuel for forward flight to gasoline for vertical flight is currently a necessary inconvenience.

6. Stator Vanes.

a. Original Design. The original duct did not include a method to straighten the swirling fan wake. The original design assumed the four vanes in the wake could control the hovering aircraft in pitch, roll, and yaw and remove the effects of engine torque.

b. Reason for Change. During the vane effectiveness testing, [Fig 3.6.1 and Fig. 3.6.2], it became clear that the vanes could not remove the torque reaction of the engine-driven fan and that stator vanes or a shroud extension would be required to prevent the aircraft from rotating uncontrollably about the thrust axis. A method to remove this torque effect was needed.

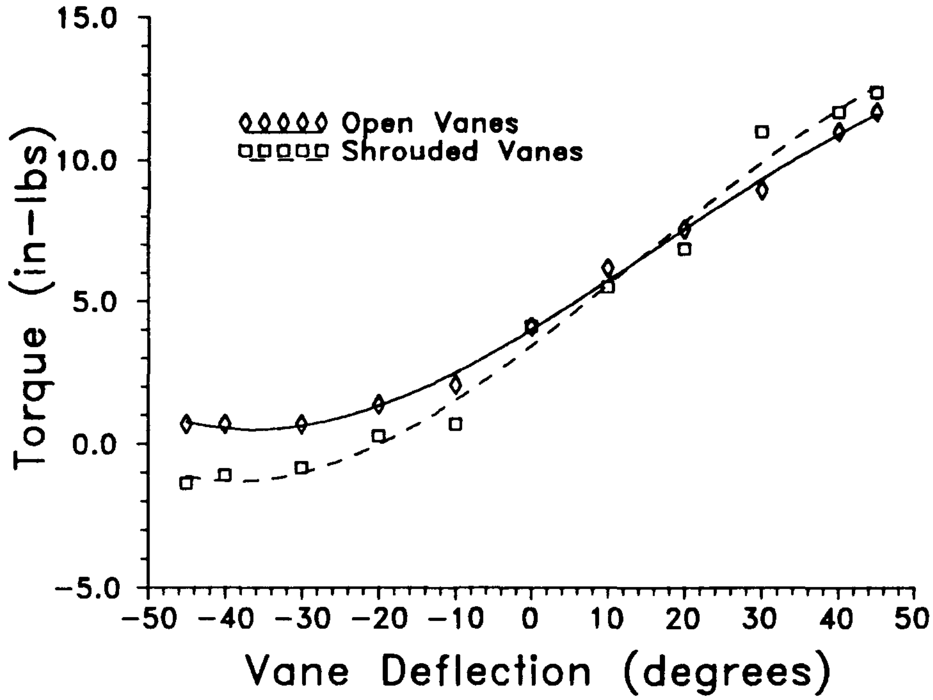

Figure 3.6.1. Torque vs. Vane Deflection Angle. OS-108 engine, 3 bladed propeller at 10,600 RPM

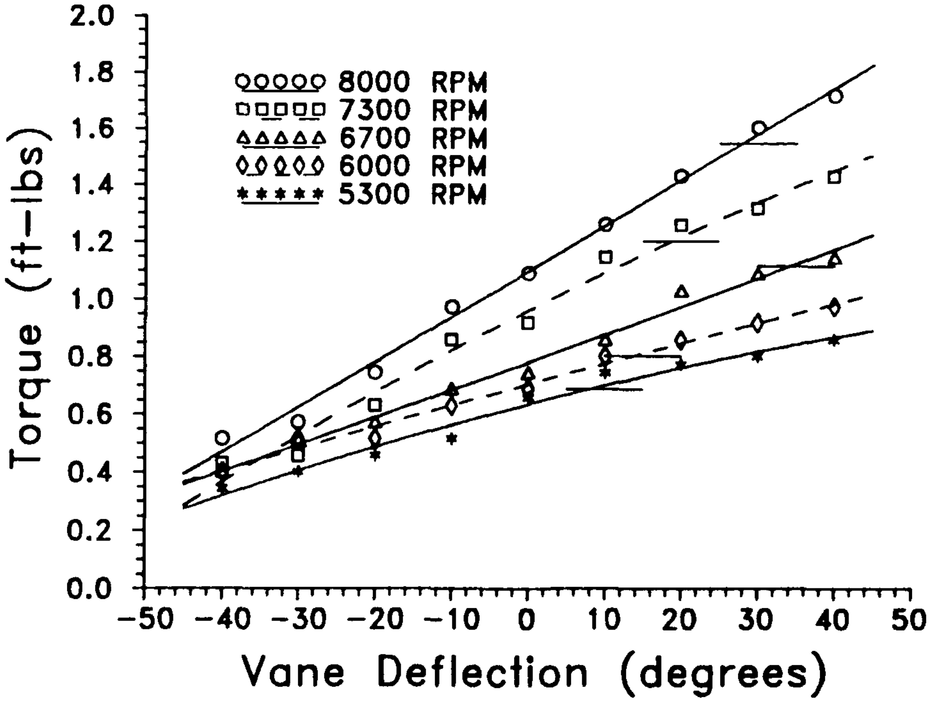

Figure 3.6.2. Torque vs. Vane Deflection Angle. Super Tartan engine, 9 bladed fan.

c. Solution. The shrouded solution was discarded because of the additional weight, and the inability to observe vane deflections during control tests. The AROD had stator vanes and unshrouded control vanes and the focus was to replicate the AROD.

Reference 5 provided guidance for designing stator vanes. This method required knowledge of propwash angle and velocity. Initially a protractor and a string on a probe in the flow measured the propwash angle. A handheld pitot-static probe positioned in the flow determined the flow velocity.

Another method to determine the propwash angle came from the plot of Torque vs. Vane Deflection (Fig. 3.6.2). With the control vanes removed, torque measurements were obtained at five RPM settings from idle to full throttle. The torques (without control vanes) were plotted as horizontal lines intersecting the common RPM curves on Figure 3.6.2. Since the control vanes were symmetric, the point of intersection indicated where the propwash had zero angle of attack with the control vanes; the vane deflection was thus the flow angle. The flow angles were cross-plotted with RPM in Figure 3.6.3. At 8000 RPM the flow angle was 28 degrees compared to the estimated 15-degree angle measured by the string and protractor method. The 15-degree angle was

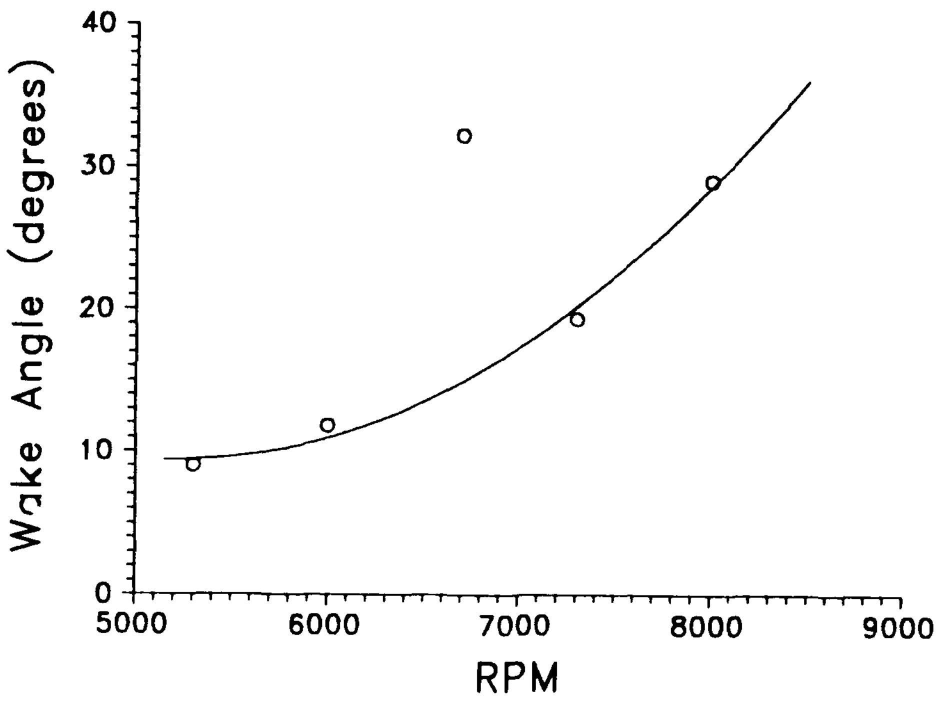

Figure 3.6.3. Wake Angle vs. RPM.

difficult to obtain with any accuracy due to the tail of the string flapping about in the propwash.

The pitot-static probe measured dynamic pressure in units of inches of water. Air density was obtained from the local airport (less than one-half mile distant). Knowing air density and from incompressible flow theory ,that indicated pressure equals dynamic pressure ($\Delta p = q = \rho V^2/2$), the velocity was estimated. Figures 3.6.4 and 3.6.5 show the measured pressure at various RPM settings and the calculated propwash velocity respectively.

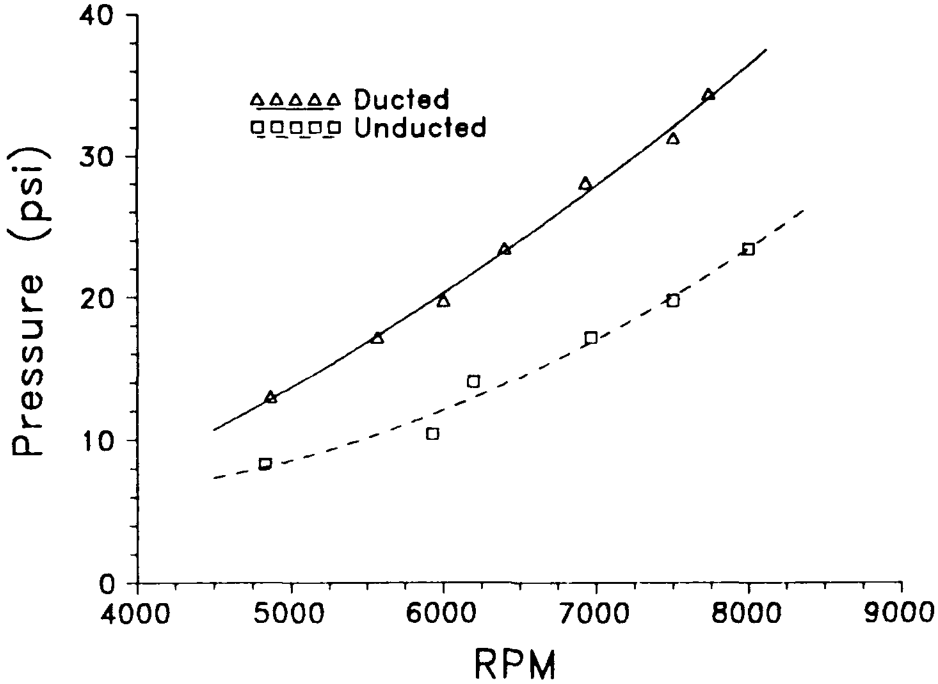

Figure 3.6.4. Pressure vs. RPM

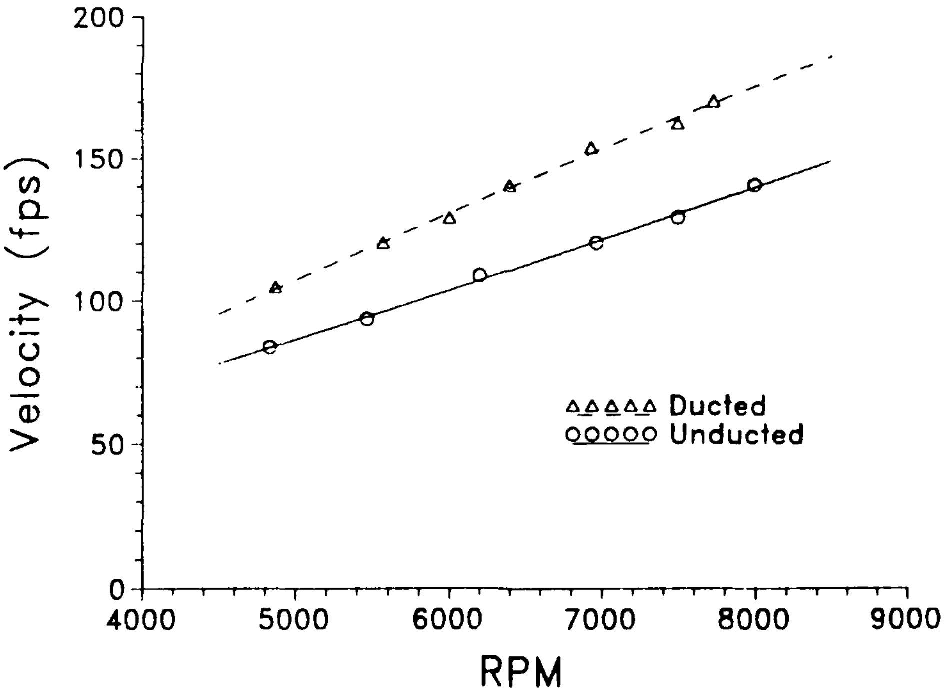

Figure 3.6.5. Velocity vs. RPM.

In selecting the camber angle (angle between airfoil camber leading edge tangent and trailing edge tangent), the unshrouded curve from Figure 3.6.1 was used. Thirty degrees was the lowest angle near the zero torque line, hence a 30 degree-camber angle was chosen. Reference 5 recommended the use of an airfoil less than 10 per cent thick to keep vane drag to a minimum.

The stator vane shape was a NACA 0010 airfoil superimposed upon a 30-degree circular arc camber line. The vane chord was determined from the airfoil thickness. The minimum vane thickness was constrained by the diameter of the four stator vane mounting rods (0.375 inches in diameter). To meet the 10 per cent airfoil thickness criterion, the stator vane chord was set at 3.75 inches.

The procedure to compute the stator vane coordinates was:

(1) Start with the equation for a symmetric NACA airfoil [Ref. 10, pp.113]:

$$y=\frac{\pm t\cdot c}{.20}(0.29690\sqrt{x}-0.12600x-0.35160x^2+0.2843x^3-0.10150x^4)$$

Where $0 < x < 1$

t = airfoil thickness in per cent of chord

c = desired chord

(2) Knowing the desired stator vane camber angle and the chord, compute the radius of curvature for the stator vane camber line:

$$r = \frac{c}{2\sin(\theta/2)}$$

Where θ is the camber angle and c is the desired chord.

(3) Compute the stator vane coordinates from:

$$x_c = \frac{c}{2} + (r \pm y)\cos\beta$$
$$y_c = (r \pm y)\sin\beta - r\cos\left(\frac{\theta}{2}\right)$$

Where

$$\beta = \frac{\pi}{2} + \theta(.5 - x)$$

x and y are the coordinates of the non-dimensional symmetric NACA airfoil

r = radius of curvature of the camber line

c = desired chord

θ = camber angle

The lower left corner of Figure 3.3.2 details the stator vane airfoil shape.

One drawback to this design methodology was a loss of thrust if the vanes did not direct the flow along the duct axis. A plot of thrust vs. vane deflection [Fig.3.6.6] indicated that thrust was a maximum near zero vane deflection. References 8 and 9 also indicated that this result might be expected. Reference 8 provided a stator vane design

methodology whereby the tangent to the vane camber line trailing edge was parallel to the duct axis, providing maximum thrust, and the vane chord was adjusted to counter the torque. This method was discovered after the stator vanes were constructed and was not validated in this research.

Figure 3.6.6 also gave an indication of the control vane drag. The large symbols plotted thrust without any vanes installed in the duct. The presence of stator vanes in the flow reduced thrust by an average 7.9% over the four higher RPM settings.

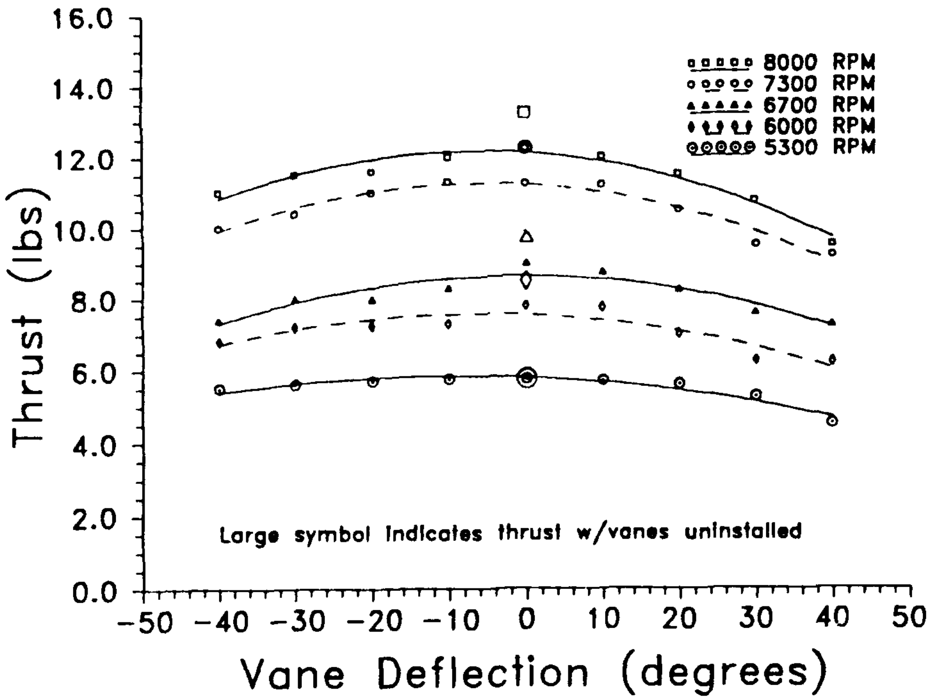

Figure 3.6.6 Thrust vs. Vane Deflection.

x and y are the coordinates of the non-dimensional symmetric NACA airfoil

r = radius of curvature of the camber line

c = desired chord

θ = camber angle

The lower left corner of Figure 3.3.2 details the stator vane airfoil shape.

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d. Construction/Incorporation. Four stator vanes were constructed of fiberglass covering blue foam with one-eighth inch plywood end plates. The foam was cut using a hot-wire method with upper and lower templates cut to the airfoil shape. The quarter-chord position of each vane was drilled out to surround the four supports.

e. Results. The vanes were not as effective as desired. Figure 3.6.7 was generated on the torque stand and shows the torque with the stator vanes set a different angles. The tangent to the stator vane trailing edges was set to the maximum deflection into the flow, approximately -25 degrees, to reduce the torque effect. Full stator vane deflection did not completely remove the torque so the control vanes were deflected approximately -30 degrees. Figure 3.6.7 shows the torque effect of the control vanes at zero deflection and at the full + and - 45 degrees deflection off the duct axis.

During the hover tests the control vane deflection to counter torque was about -15 to -20 degrees. The difference between the torque stand tests and the tethered hover tests was attributed to the propwash blockage experienced on the torque stand. Nearly half of the control vanes were directly in front of the torque stand engine mounting wheel, forcing much of the flow away from the control vanes. This situation may simulate the in-ground-effect

situation. Thus the data obtained from the torque stand is conservative; the control vanes should be more effective out-of-ground-effect than indicated by the torque stand data.

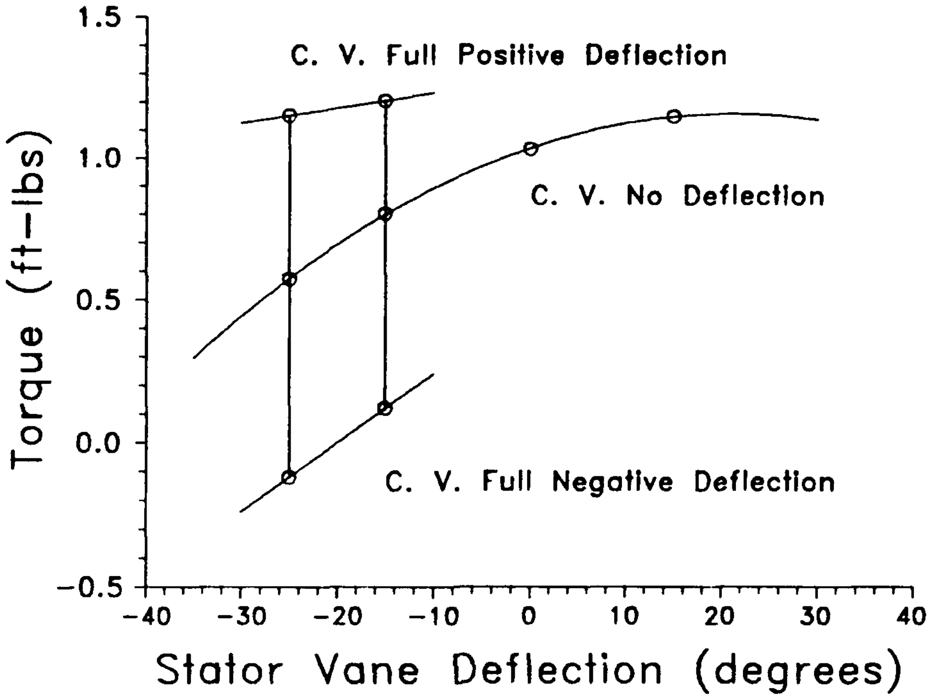


Figure 3.6.7 Torque vs. Stator Vane Deflection Angle.

The original desire for the stator vanes to counter all of the engine torque and for the control vanes to control the duct about all three axes was not met. With the control vanes preset to -20 degrees, with full motion being -65 to +25, the tethered hover flight tests demonstrated vane stall at the larger negative deflections. Several times the control vanes stalled in response to either pilot control inputs or gyro inputs, spinning the duct uncontrollably about its longitudinal axis.

f. ***Limitations.*** The stator vanes necessarily added weight to the airframe. They had a constant chord and were not tailored (e.g. varied camber and chord) to the measured flow, and were not as effective as desired.

The primary error in the vane design was the method for selecting the camber angle. Figure 3.6.2 and Figure 3.6.3 should have been used to determine a camber angle closer to -45 degrees where the curves converge near zero torque. Figure 3.6.1 should not have been used since it was not the same engine and propeller used for the hover tests. Figure 3.6.3 could have been used to select the proper stator vane angle to minimize vane drag and maximize the anti-torque effect, i.e. angle for vane airfoil L/D_{max}.

The one data point significantly different from the others in Figure 3.6.3 was possibly due to the difficulty of repeating engine RPM from one test to another. The data for each RPM curve in Figure 3.6.3 was collected after setting an RPM near the desired RPM then taking the data. Possibly the 6700 RPM curve was actually less than 6700 and the no-vane data point was taken at a greater RPM. When the data were cross plotted, the combination of the two errors may have produced the widely varying data point in Figure 3.6.3.

Another limitation to the stator vane design was the method for setting the vane angles. Friction of control

vane hardware against the engine mounting plate held the vanes in position. Friction did not hold two of the vanes at the desired angle with engine running. During several of the engine tests, the vanes moved from the set angle reducing the counter-torque effect. A better method to set the vane angle should be developed.

7. Duct Vane Controls.

a. Original Design. References 1 and 2 did not discuss control vane integration in the ARCHYTAS design. The control vanes were affixed to Futaba control servos mounted in the duct center section. The original design required only connecting these servos to a receiver and designing the appropriate control surface mixing.

b. Solution. The radio control system used for the half-scale ARCHYTAS was a Futaba PCM 1024A (Pulse Code Modulation) type radio with eight control channels designed for RC model airplanes. Table 3.7.1 lists the channel assignments. In the airplane mode, conventional ailerons, rudder, flaps, elevator, and throttle channels were used without control surface mixing.

In the vertical mode, special control surface mixing accomplished the desired control vane movements. Each vane was connected to a radio channel. The mixing settings are listed in Appendix C. The Futaba radio had five pre-

programmed control mixes and four other optional program mixes.

Table 3.7.1 FUTABA RADIO CHANNELIZATION.

Channel	Function
1	Aileron
2	Elevator
3	Throttle
4	Rudder
6	Flaps

In the vertical mode, the four control vanes were each assigned a radio channel. To control the duct in fore-and-aft pitch, the elevator (channel 2) and flaps (channel 6) were assigned to opposite vanes. For side-to-side pitch (hereafter denoted yaw), the rudder (channel 4) and aileron (channel 1) were assigned to the other opposing vanes. The transmitter programmed the channel 2 and 6 vanes to operate together for pitch control and the channel 1 and 4 vanes to operate together for yaw pitch control. For roll control about the duct axis, channels 1, 2, and 6 were slaved to channel 4 so all four vanes moved together with the rudder channel command.

Clearly, transitioning from the vertical to the horizontal duct position was beyond the capability of the current control system due to the incompatibility between the

vertical and horizontal flight controls requirements. For example, duct roll is airplane yaw, for the vertical duct, and airplane roll in the horizontal position. Similarly, duct yaw is airplane roll or airplane yaw depending on the duct position. The Futaba radio can save the control programs for either configuration but can not operate both programs concurrently or transition smoothly between them.

c. Construction/Incorporation. The control integration was accomplished through the Futaba transmitter which had enough mixing options to control the duct manually about all three axes. It was not possible to incorporate rate stabilization about any of the axes without losing the ability to control the vehicle in the other axes due to the limitations of the radio and servos.

A rate gyro takes its input from the roll channel and provides output to all four vanes. With a rate gyro incorporated, three of the four vanes do not receive input from their usual channels to control either fore-and-aft or side-to-side pitching.

A rate gyro was incorporated into the duct longitudinal roll axis to counter the engine torque but, as mentioned, control about the other axes was surrendered. To test this roll control, the vehicle was mounted on a modified RC-model helicopter test stand that restrained the pitch or

yaw movement but allowed vertical movement and roll about the duct thrust axis.

In another test, the duct was constrained in roll on a two-degree-of-freedom test stand and allowed to pitch and yaw. Pitch rate stabilization was not possible. Since the servos do not allow response reversal, the pitch rate gyro can not operate two vanes together to cause a restoring pitch moment.

d. Results. For testing, the duct was placed vertically on an RC-model helicopter training stand that allowed the duct to rotate about its roll axis and to translate vertically. The initial test proved the requirement for roll rate stabilization. Without stabilization, controlling the duct heading required extreme pilot concentration to compensate for throttle setting changes or intermittent engine torque changes. After roll rate stabilization was incorporated, the duct was stable and controllable in roll providing the roll rates remained low. When a fast roll rate built up opposite the propeller direction, the rate gyro commanded full vane deflection resulting in vane stall and uncontrolled roll.

The duct was also tested on a two-degree-of-freedom test stand that allowed the duct to pitch and yaw but not roll. The duct was positioned horizontally in the test

stand and both the vertical pair and the horizontal pair of control vanes were moved to adjust the pitch attitude. The duct was extremely sensitive but controllable in pitch and yaw.

This test also demonstrated the coupling between the pitch and yaw. When actuated, the vertical pair of vanes yawed the duct and affected the pitch attitude. The test stand had significant friction and inertia forces that adversely affected the ability to observe the coupling of the horizontal pair of control vanes to yaw movement but due to the similarity between the two axes and controls, the responses were assumed alike. For successful free flight, rate gyros will be required to provide artificial stability in all axes [Ref. 2, 11, 12, 13, and 14].

e. Limitations. The Futaba RC control system was the limiting factor in the flight controls due to a combination of servo/gyro characteristics, the current servo/vane configuration, and radio mixing limitations. The Futaba system was not designed to control an unconventional vehicle such as the ARCHYTAS duct. In addition to the limitations discussed in the previous paragraphs, there was not enough capability to couple a longitudinal roll input to the throttle to automatically remove any torque fluctuation from changing throttle settings. Neither was it possible to

combine rate gyro inputs with pilot control inputs about all three axes. These features require a multi-input multi-output (MIMO) controller that should be incorporated into the full-scale ARCHYTAS control system.

To make the Futaba system work requires only two changes: (1) adding servos to the stator vanes to stabilize the longitudinal roll; and (2) finding a way to reverse the response of an individual servo. The duct center section would require modification to install four more servos for the stator vanes, which would move in response to the roll gyro stabilized radio channel. Once a servo response can be reversed, the control vanes would require mixing to provide control and stability to both pitch axes.

8. Miscellaneous Enhancements.

a. Vertical Stabilizer. Originally, control cables transmitted control inputs from the rudder servos to the rudders. The cable ran through a small tube glued to the inside of the tail booms, preventing the cables from bending. Removing the tail section to transport the aircraft was difficult because of the glued control tube.

The control cables and tubes were replaced by stiffer copper welding rods in a control tube that slid easily into the tail booms for simple, quick removal and

installation. A similar set of control rods was also made for the short-tail configuration.

With these two improvements, the half-scale ARCHYTAS was easily convertible between the short-tail and the long-tail configurations.

b. Weight Distribution. The original configuration contained a heavy 4000 mA four C-cell battery pack located aft of the nose wheel. The replacement was a 1200 mA four cell battery pack of nearly half the weight, positioned forward of the nose wheel. Weight was eliminated leaving the center-of-gravity relatively unchanged.

Other weight saving measures included:

(1) removing excess material from the access plate mounting tabs which also provided better accessibility to the compartments.

(2) replacing steel bolts with nylon bolts.

Overall weight savings totalled approximately one-half pound.

IV. AIRCRAFT CHARACTERISTICS

A. DIMENSIONS.

Three-view drawings of the vertical and horizontal configurations of the half-scale ARCHYTAS are shown in Figures 4.1 through 4.5. Figures 4.6 and 4.7 are photographs of the actual half-scale ARCHYTAS in both configurations. Figure 4.8 shows the location of the various equipment bays in the aircraft. The forward bay houses the battery, nose wheel steering servo, and the radio receiver. The next bay aft is available for the flight data telemetry system [Fig. 4.9]. The bays on either side of the duct house one fuel tank and one rudder servo each [Fig. 4.10]. Table 4.1 details several important dimensions of ARCHYTAS.

Table 4.1 ARCHYTAS DIMENSIONS.

Duct Chord		12 in.
Duct TE to control vane 1/4 chord		2.1875 in.
Duct inside diameter		11.5 in.
Duct outside diameter		12 in.
Bellmouth outside diameter		16 in.
Control Vane Chord		3 in.
Stator Vane Chord		3.75 in.
Length	Long tail	5 ft
	Short tail	3.5 ft
Wing Span		6 ft
Weight (Super Tartan w/fuel)		29.4 lbs.

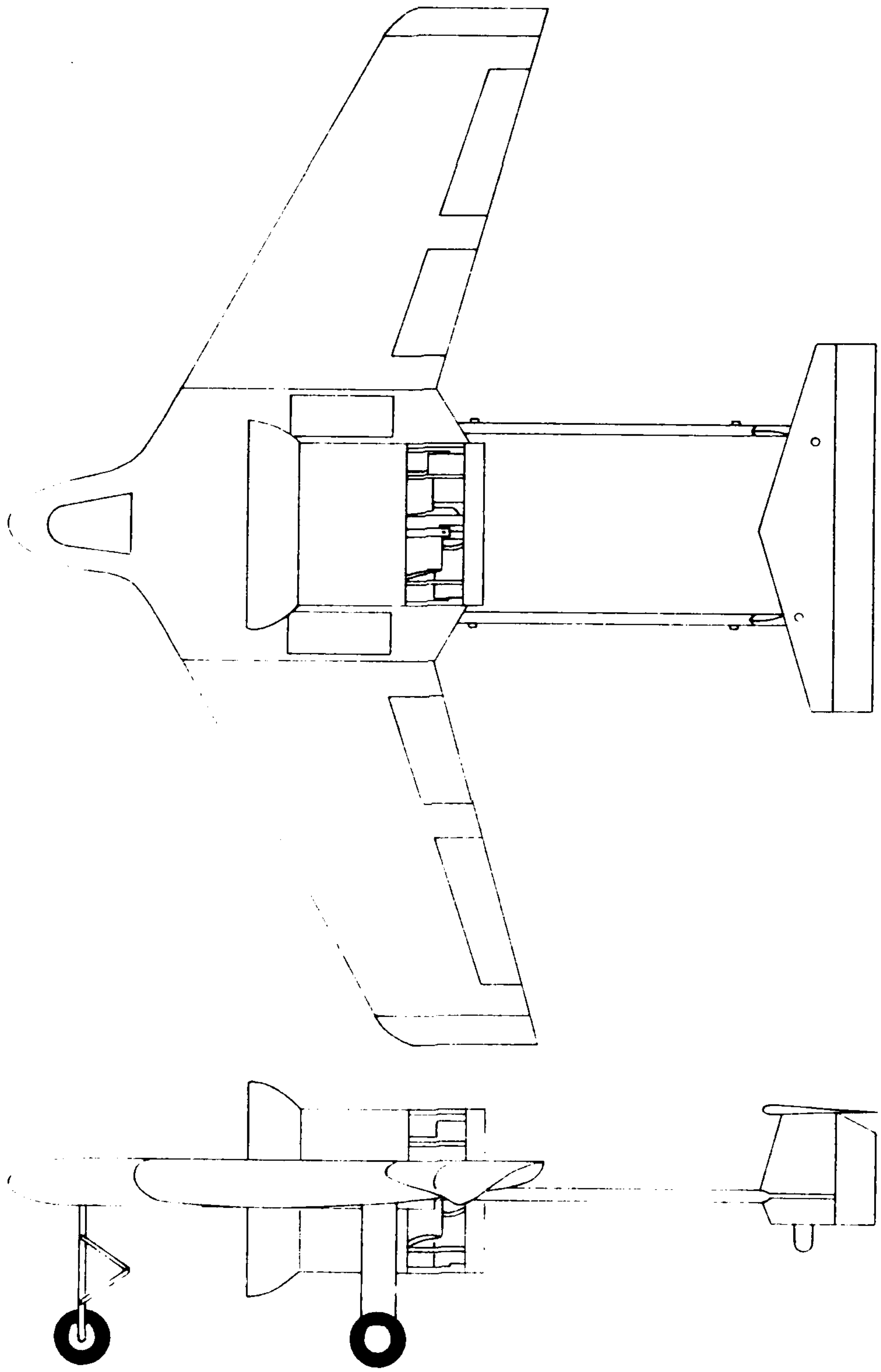


Figure 4.1. Top and Side View Horizontal Flight Configuration.

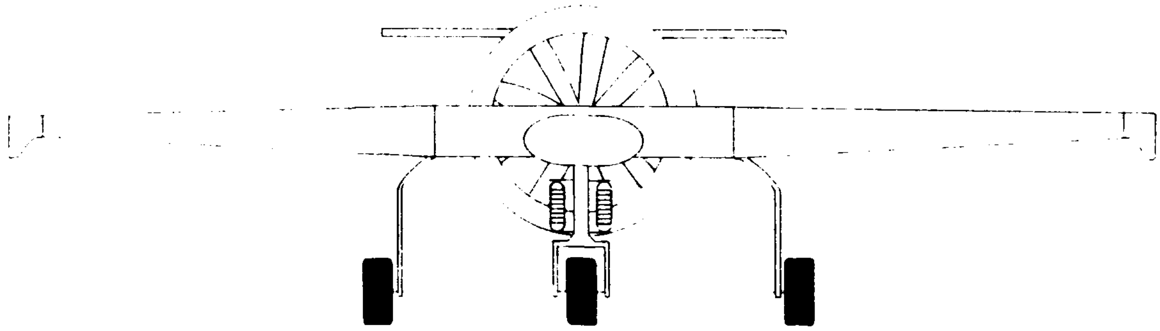


Figure 4.2. Half-Scale ARCHYTAS Front View,
Horizontal Flight Configuration.

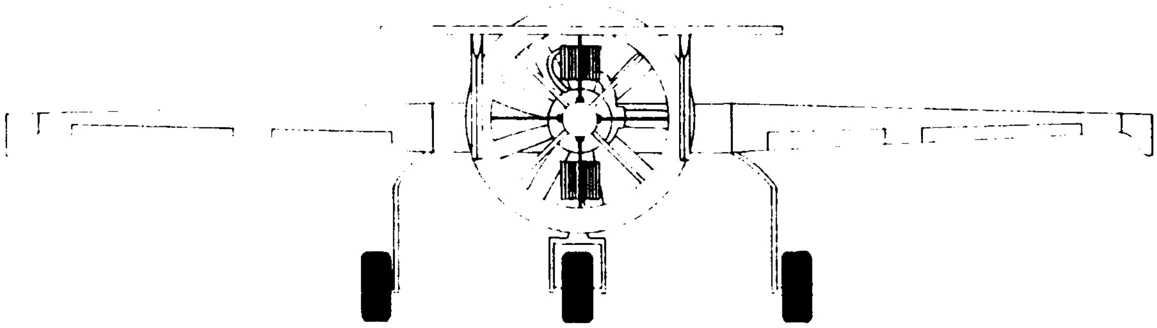


Figure 4.3. Half-Scale ARCHYTAS Rear View,
Horizontal Flight Configuration.

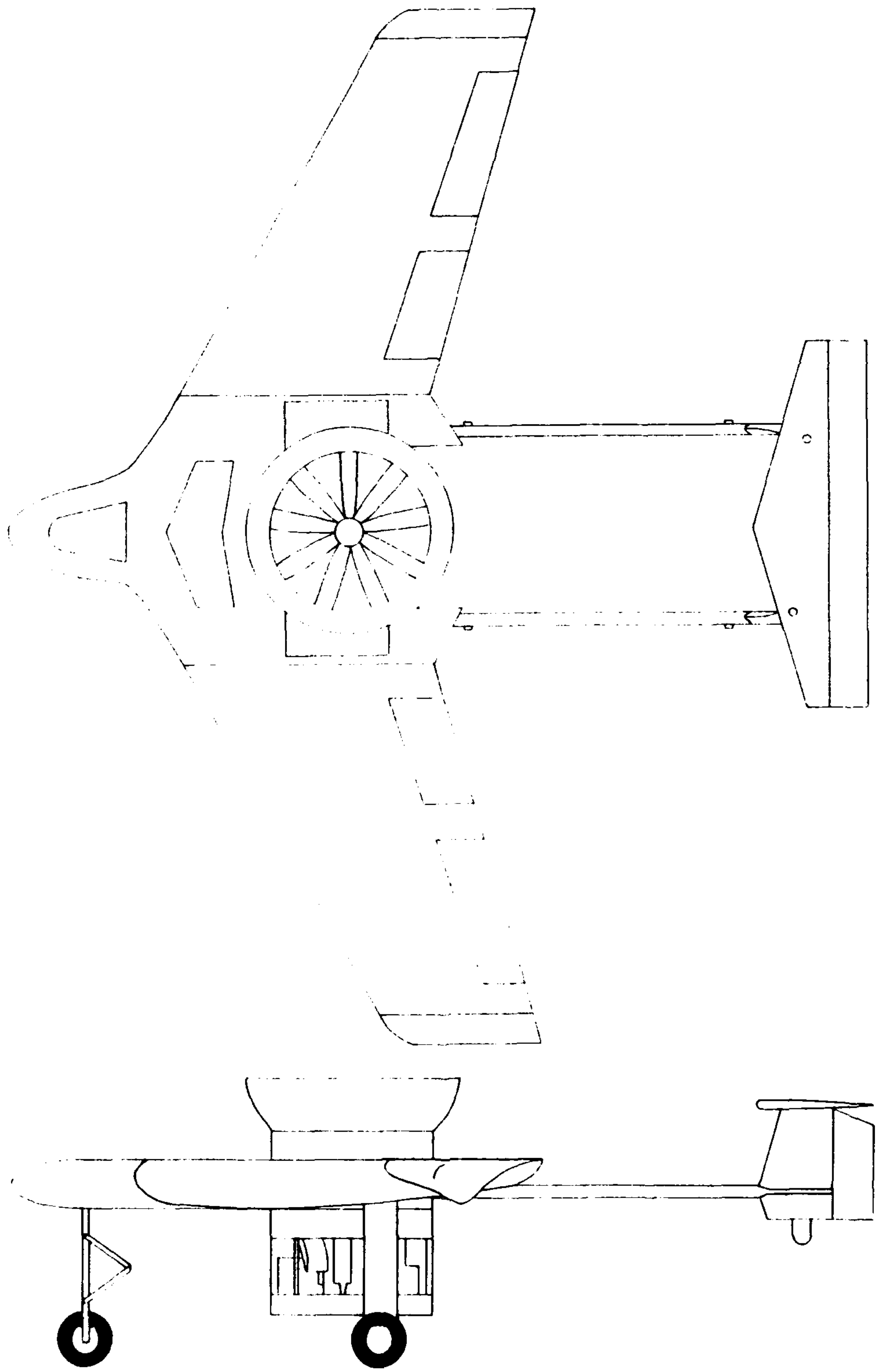


Figure 4.4. Top and Side View Vertical Flight Configuration.

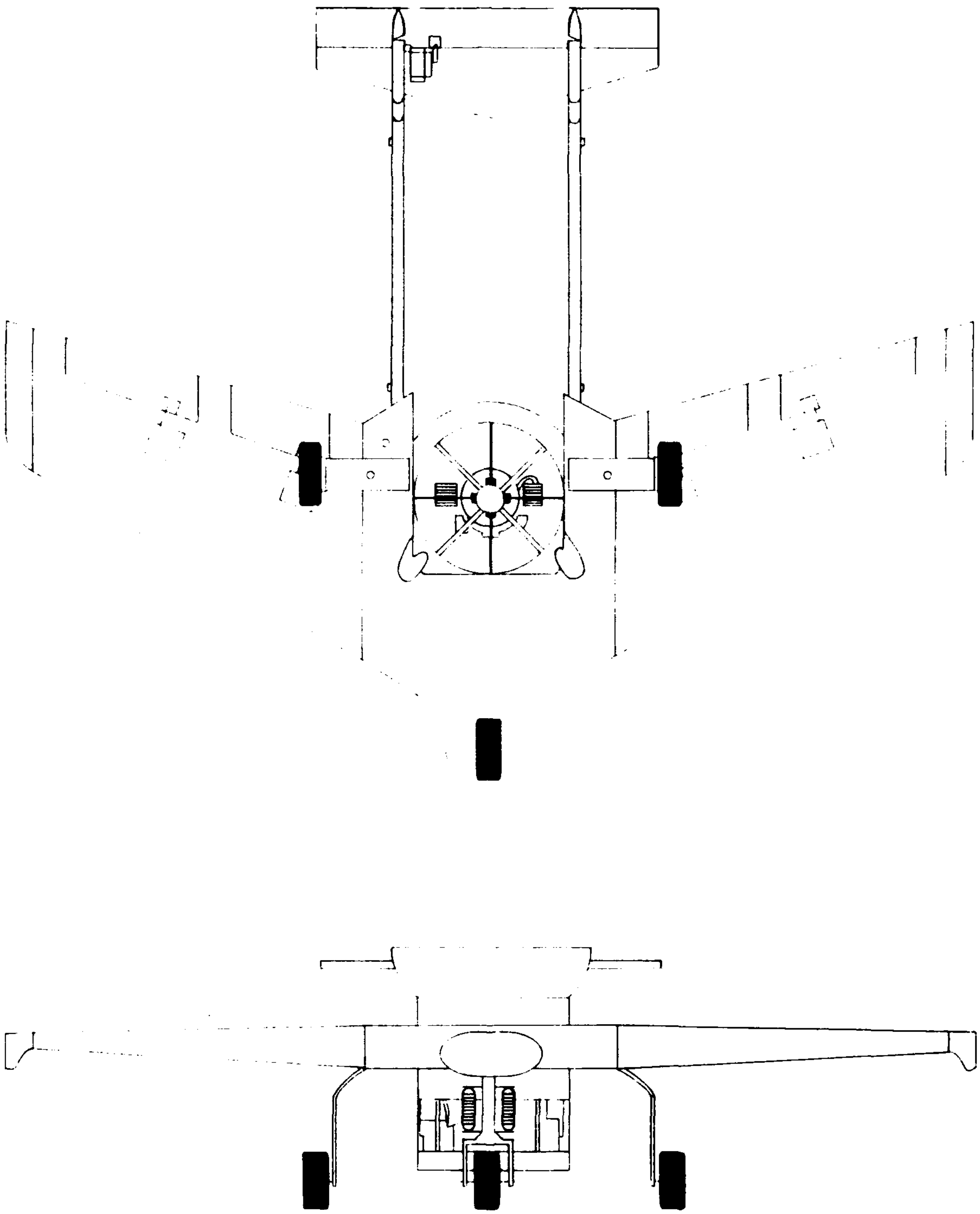


Figure 4.5. Half-Scale ARCHYTAS Bottom and Front View.

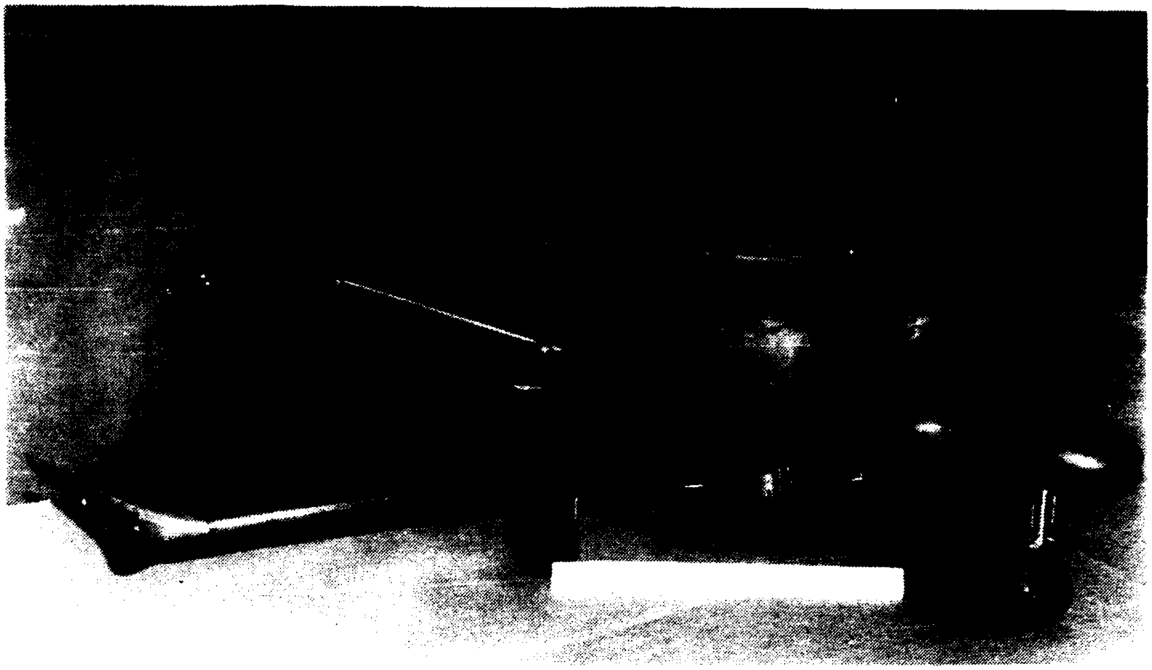


Figure 4.6. Half-Scale ARCHYTAS Vertical Flight Configuration.

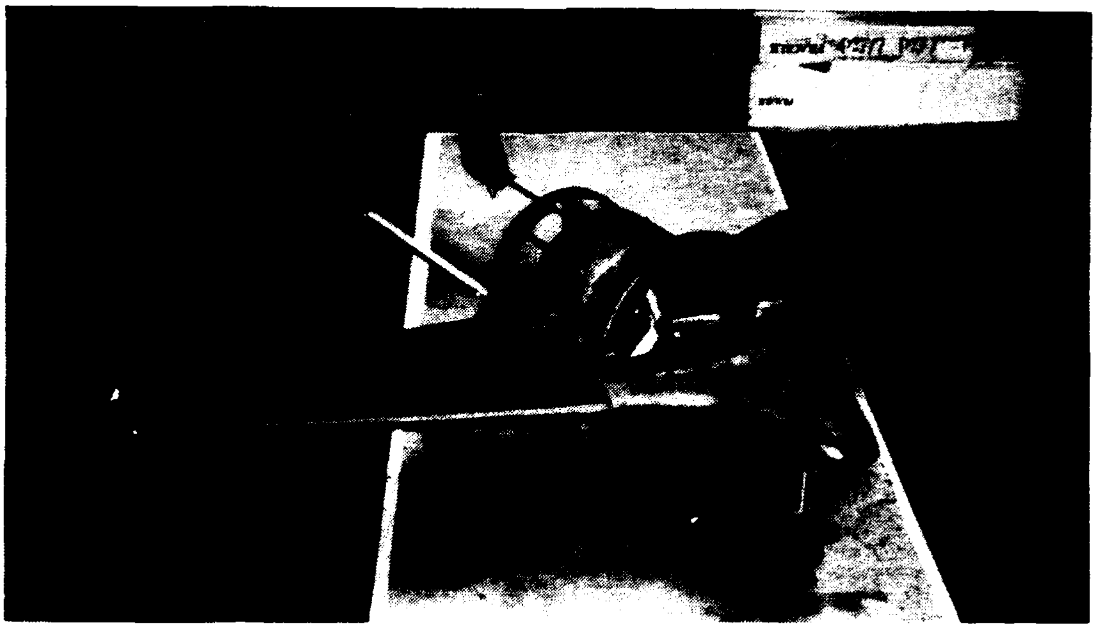


Figure 4.7. Half-Scale ARCHYTAS Horizontal Flight Configuration.

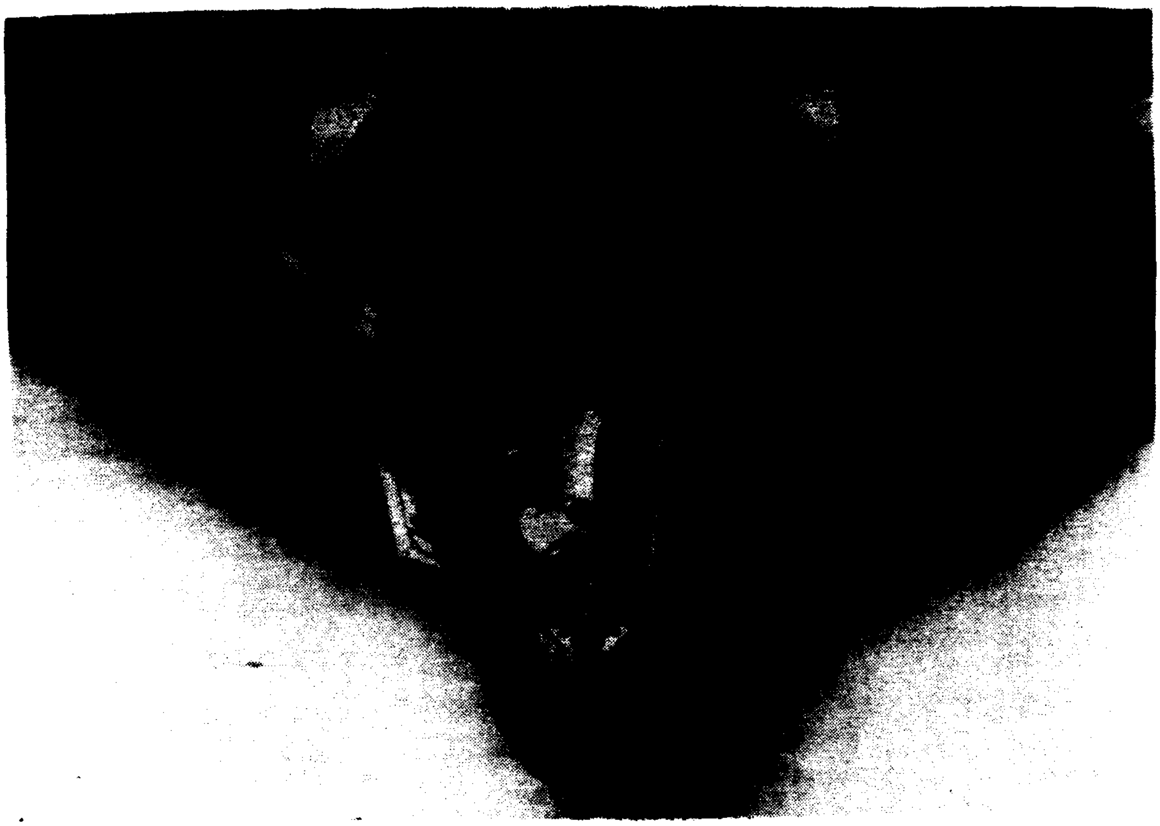


Figure 4.8. Equipment Bays.

Figure 4.9. Telemetry Bay.

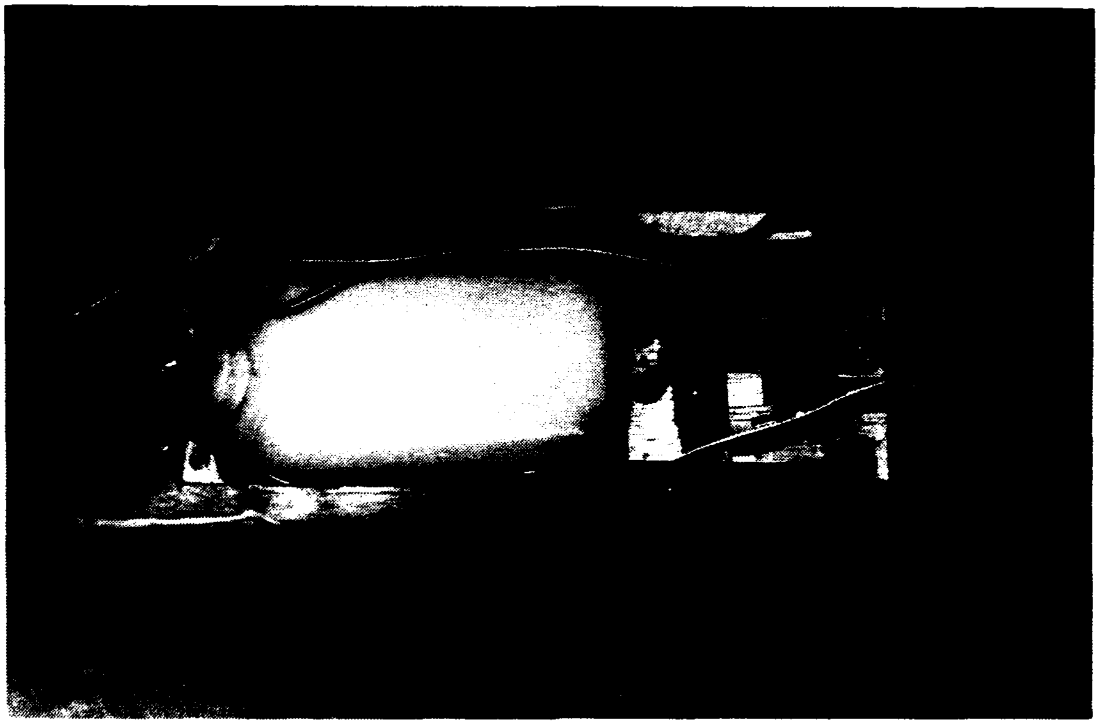


Figure 4.10. Left Side Bay
(Fuel Tank and Rudder Servo).

B. CENTER OF GRAVITY CALCULATIONS

Datum for center-of-gravity calculations was established as the aircraft nose. The landing gear positions from datum measured: nose gear - 4.3125 inches, mainmounts - 26.625 inches. A portable scale was used to determine the weight on each wheel. Ellwood [Ref. 2, pp.22] determined the mean aerodynamic chord (MAC) to be 15.28 inches. The MAC leading edge was 19.47 inches aft of datum and 25% MAC was 23.29 inches aft of datum [Fig. 4.14].

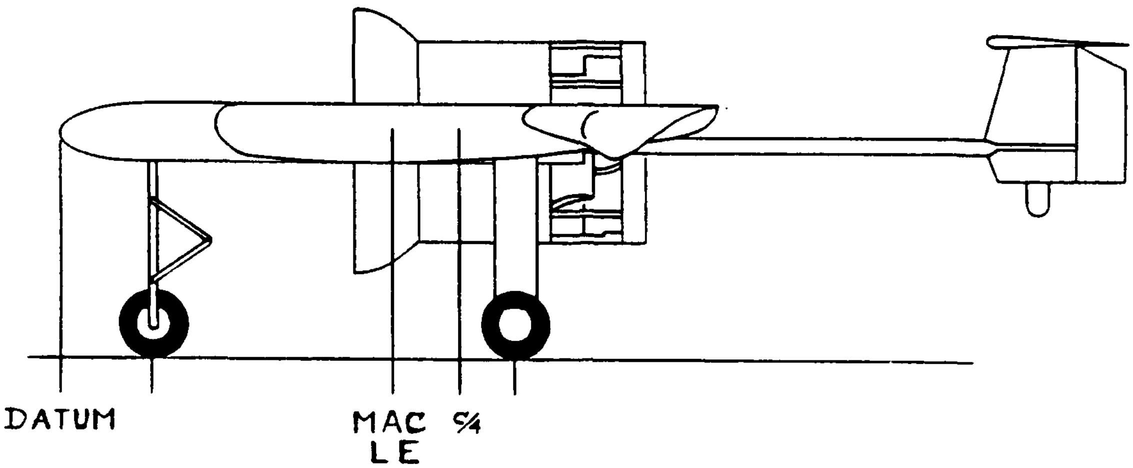


Figure 4.11. ARCHYTAS Datum Plot.

The calculation of center-of-gravity position in % MAC was determined by:

$$\%MAC = \frac{\frac{\sum W_i A_i}{\sum W_i} - A_{MACLE}}{MAC}$$

Where: %MAC is the center-of-gravity location on the MAC.

W_i is the weight recorded on a wheel.

A_i is the moment arm for a wheel.

W_iA_i is the moment contribution of each wheel.

MAC is the Mean Aerodynamic Chord 15.28 inches.

A_{MACLE} is the location of the MAC leading edge.

For convenience, Fig. 4.12 locates the center-of-gravity datum on the MAC.

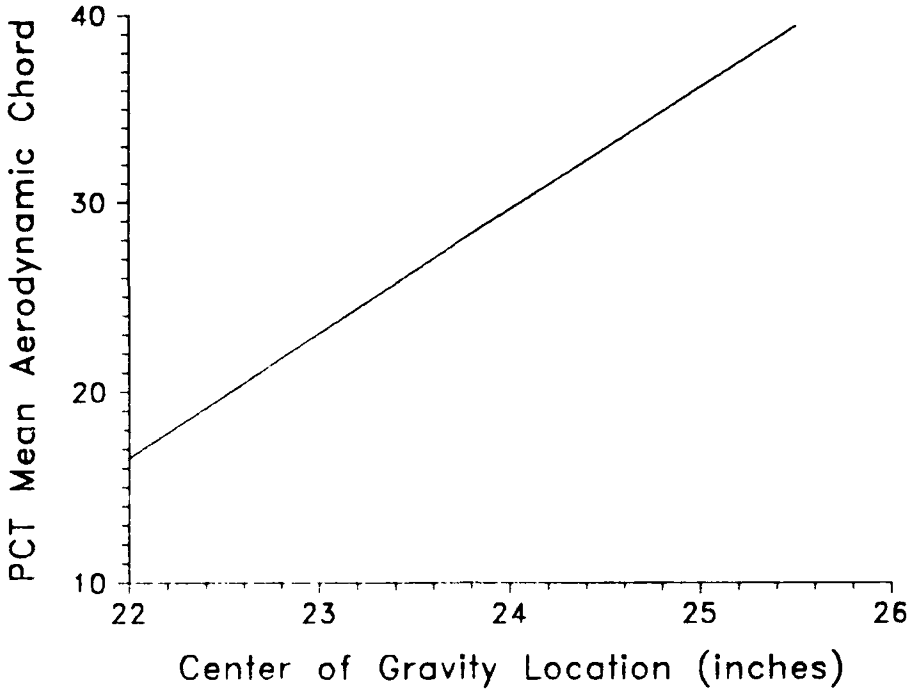


Figure 4.12. Center-of-gravity vs. % MAC.

C. MOMENTS OF INERTIA CALCULATIONS.

To design a multi-input multi-output controller, estimates for the moments of inertia are required. Reference 15 describes the method used to obtain the pitching, rolling, and yawing moments of inertia for the half-scale ARCHYTAS and estimates for the full-scale ARCHYTAS.

Using the method described in Reference 15, the half-scale ARCHYTAS was suspended from a single point at the ceiling by two cords [Fig. 4.16] and oscillated in the desired plane.

Three tests were done in each axis and the time for five oscillations averaged to obtain the period. From the parallel axis theorem the moment of inertia was determined by:

$$I_{cg} = Wl\left(\frac{T^2}{4\pi^2} - \frac{l}{g}\right) - I_0$$

where: I_{cg} = Moment of Inertia (either I_{xx}, I_{yy}, I_{zz})

W = Weight, 29.39 pounds

l = Distance from pivot point to model c.g., feet

= 11 ft 0 in. for pitch

= 10 ft 0 in. for roll

= 7 ft 11.5 in. for yaw

T = Period of oscillation

= 3.7 seconds for pitch

= 3.5 seconds for roll

= 3.2 seconds for yaw

g = 32.2 ft/s^2

I_0 = moments of inertia of various aircraft parts about their individual c.g. locations, usually less than one percent of I_{cg} for most aircraft, and was neglected.

The aircraft weight included the Super Tartan engine, the nine-bladed fan and a simulated fuel load consisting of lead weights placed near the fuel cell. The ducted fan was in the vertical flight position to determine the moments of inertia.

Moments of inertia scale by the fifth power, so the estimates for the full-scale moments of inertia are the product of the measured moment of inertia (of the half-scale)

and 2^5 or 32. The moments of inertia for ARCHYTAS are in Table 4.2.

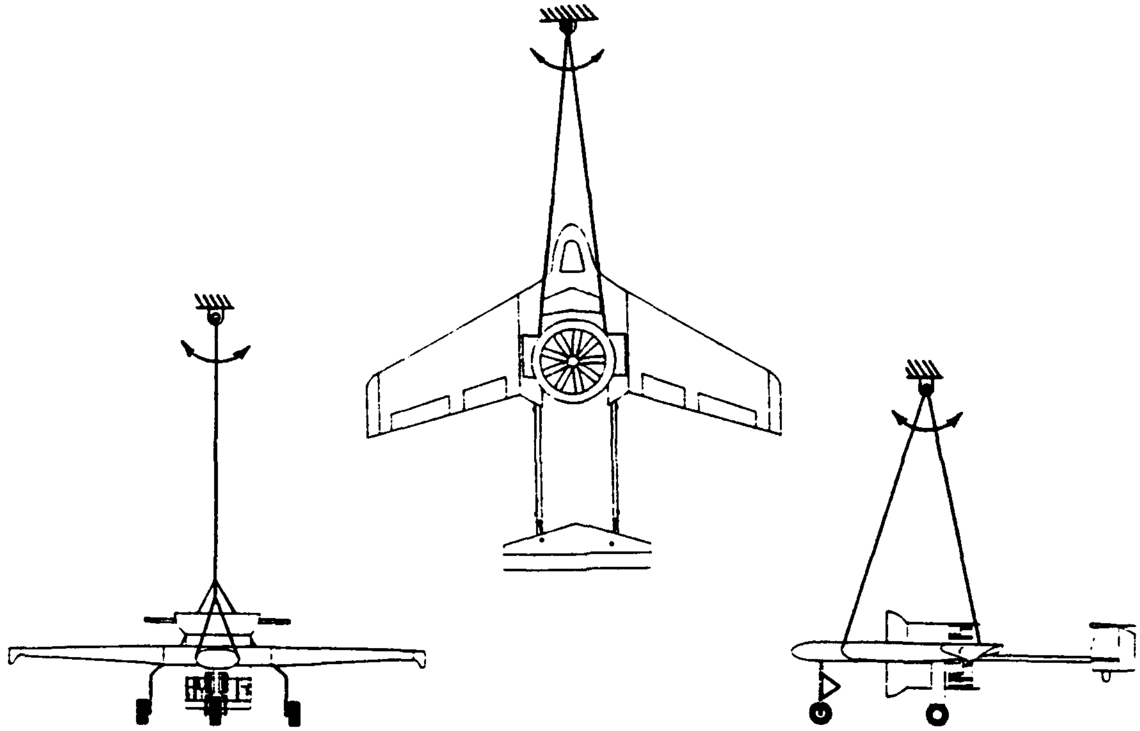


Figure 4.16 Moments of Inertia Test Configurations.

Table 4.2. ARCHYTAS' MOMENTS OF INERTIA (SLUG-FT^2)

	Half Scale	Full Scale
Pitch I_{yy}	2.40	76.80
Roll I_{xx}	1.18	37.69
Yaw I_{zz}	2.41	77.12

V. CONCLUSIONS AND RECOMMENDATIONS

A. CONCLUSIONS.

The desired goal of this investigation was to fly a half-scale ducted fan Unmanned Aerial Vehicle (UAV) in horizontal and vertical flight as a proof of concept for a full scale UAV of similar design.

The following items were investigated:

1. Methods to increase thrust from the ducted fan propulsion system.

2. The effectiveness and coupling of the four control vanes in controlling the vehicle in vertical flight (pitch, roll, and yaw) and in countering the engine torque.

3. The design requirements of stator vanes to counter engine induced torque effects.

This investigation accomplished the following:

1. The duct sustained a controlled tethered hover.

2. An effective bellmouth increased thrust from the installed powerplant.

3. A nine-bladed fan provided sufficient thrust to fly the ducted-fan in a tethered hover.

4. Engine power characteristics were determined.

5. The control vanes and stator vanes were integrated to provide manual three-axis control.

6. Gyro stabilization was integrated into the roll axis controls allowing a controlled tethered hover.

7. New landing gear were designed and installed.

The overall performance of the half-scale UAV was improved upon. Thrust was increased for the same engine and propeller combination. A control system was developed to investigate (1) the control vane and stator vane effectiveness, (2) control vane cross-coupling, and (3) tethered hover characteristics.

The UAV was not flown horizontally due to the lack of a safe airfield to fly an untested vehicle. The complete vehicle was not flown vertically untethered due to insufficient thrust and the lack of a stabilized, integrated vertical flight control system.

B. RECOMMENDATIONS FOR HALF-SCALE ARCHYTAS

1. Continue with modifications and improvements prior to implementation of similar changes to the modified AQUILA such as:

a. Design a fan optimized for the engine and duct.

b. Obtain a small engine that will produce 6 HP at 12000 RPM.

c. Redesign the duct center section as follows:

1. Modify the engine mount to position the propeller plane at the duct one-quarter chord.

2. Gyro stabilize the stator vanes to remove engine torque.

3. Gyro stabilize the control vane movement in the fore-and-aft and side-to-side directions.

4. Redesign the center section supports to position the control vanes entirely in the propwash.

5. Extend the duct chord to at least the control vane quarter-chord position for maximum vane effectiveness.

e. Redesign the stator vanes to more effectively counter engine torque using the Reference 8 computer code.

f. Design a more efficient fan for the installed engine using the Reference 8 computer code.

2. Flight test the vehicle with all tail configurations and with control vanes slaved to rudder and elevator movements.

3. Install angle of attack, sideslip angle and airspeed sensors and telemetry equipment and conduct test flights to generate estimates of full-scale vehicle flight characteristics.

4. Flight test the various control mixings, e.g. flaps mixed with ailerons, rudder mixed with ailerons, etc..

C. RECOMMENDATIONS FOR FULL-SCALE ARCHYTAS.

1. Build a ducted propulsion unit with following features:

a. Design a bellmouth using the $r = \sin 2\theta$ method.

b. Incorporate proper anti-torque vanes in the duct.

c. Use Hovey's method to calculate duct size using powerplant data and thrust required.

d. Incorporate features allowing easy engine fine tuning and adjustment while the engine is installed and running in the duct.

e. Provide engine adapters for the thrust and torque test stands.

f. Fair-in fuel lines and control vane cable runs.

g. Design airfoil-shaped supports between duct and engine mounts to reduce drag.

2. Due to the complications of mixing the controls and the conversion between the hovering and horizontal flight of a tilting ducted fan, consider and investigate a tail-sitter configuration where the duct is fixed in the airframe and sits on its tail for launch and recovery. The whole vehicle would pitch forward for horizontal flight. An additional advantage of the tailsitter over the tilting ducted fan is the elimination of the tilting controls and mechanism for an expected weight saving.

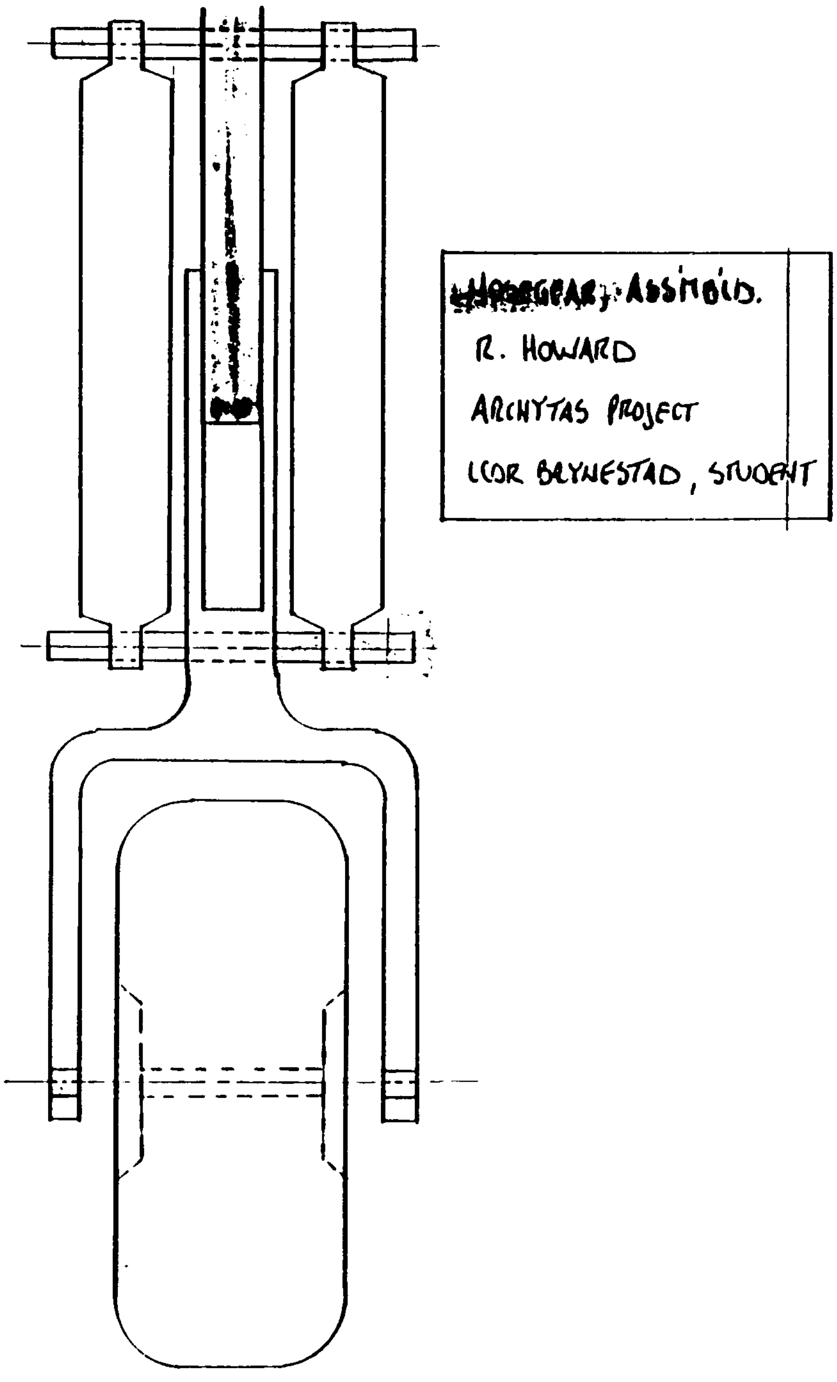
D. UAV LABORATORY RECOMMENDATION

1. Design and build a convenient small engine test stand that will concurrently and accurately measure and record thrust, torque, and engine RPM. It should be easily adaptable to all engine mount configurations and should be able to maintain a constant engine RPM.

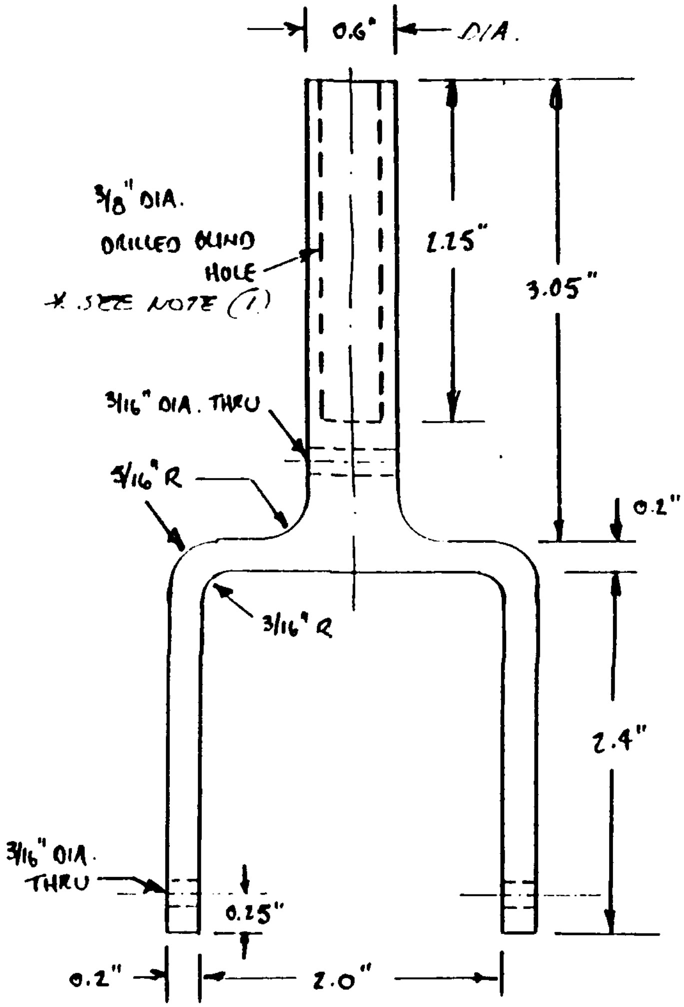
A ducted-fan type vehicle has a large potential to fulfil Navy requirements for the VIPER UAV role due to its safe, efficient, and versatile operating characteristics. Further research will quantify the performance characteristics of such a vehicle and provide significant insight for the follow-on design and construction of a ducted-fan UAV.

APPENDIX A

LANDING GEAR DESIGN



FORK

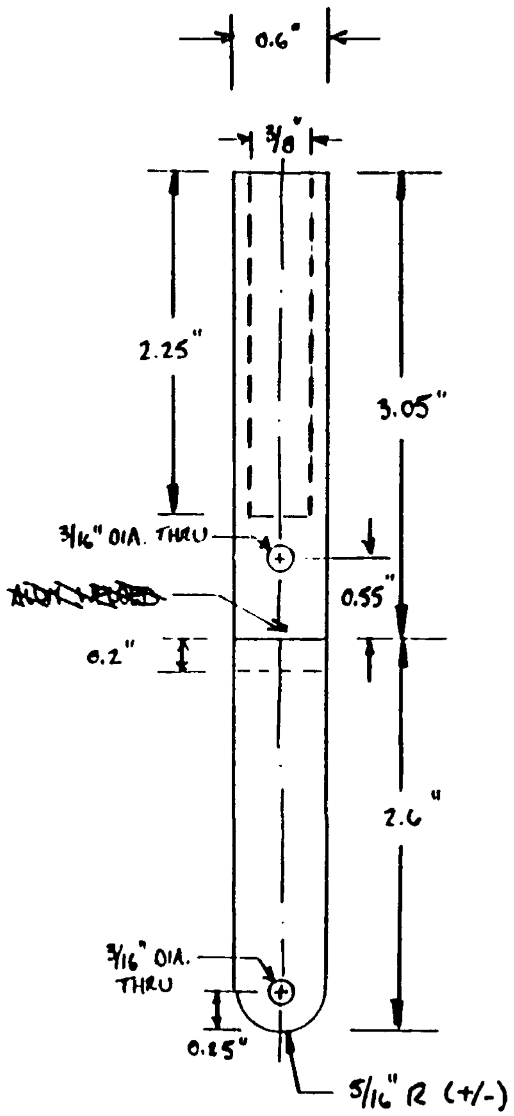


MAT'L: ALUM.

NOTE: BLIND HOLE FOR SLIDING FIT W/ 3/8" DIA. ROD.

FULL SCALE

FRONT VIEW



NOTE: 3/8" HIDDEN LINES INDICATE A DRILLED BLIND HOLE, 3/8" DIAM., TO FIT SLIDING ROD.

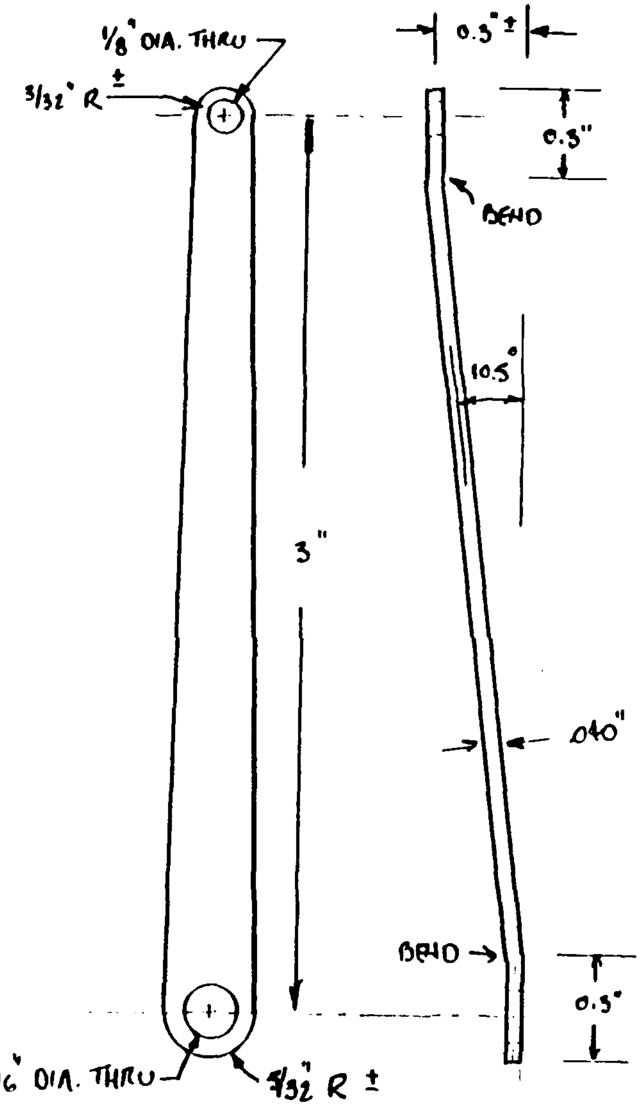
MAT'L: ALUM.

FULL SCALE

SIDE VIEW

NOSEGEAR ADDENDUM

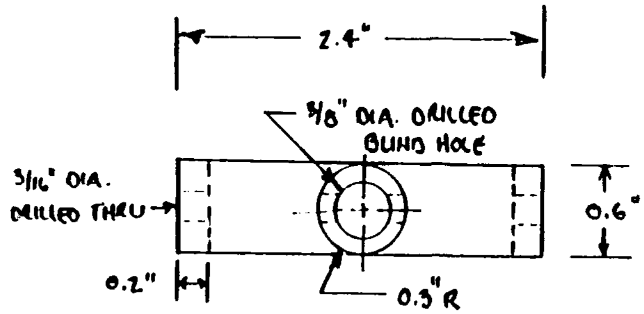
ARCHYTAS
R. HOWARD
3/20/91



SCALE: 2 TIMES REAL LIFE!

NOTE: STEEL STOCK ≈ 0.040" (THINNER OR THICKER?)

* TO BE USED FOR TRAILING LINKAGES ON NOSEGEAR.
* NEED FOUR; LENGTH NOT CRITICAL, BUT MUST BE IDENTICAL.



NOTE: 3/8" BLIND HOLE FOR SLIDING FIT OF 3/8" ALUM. ROD.

FULL SCALE

TOP VIEW

NOTES

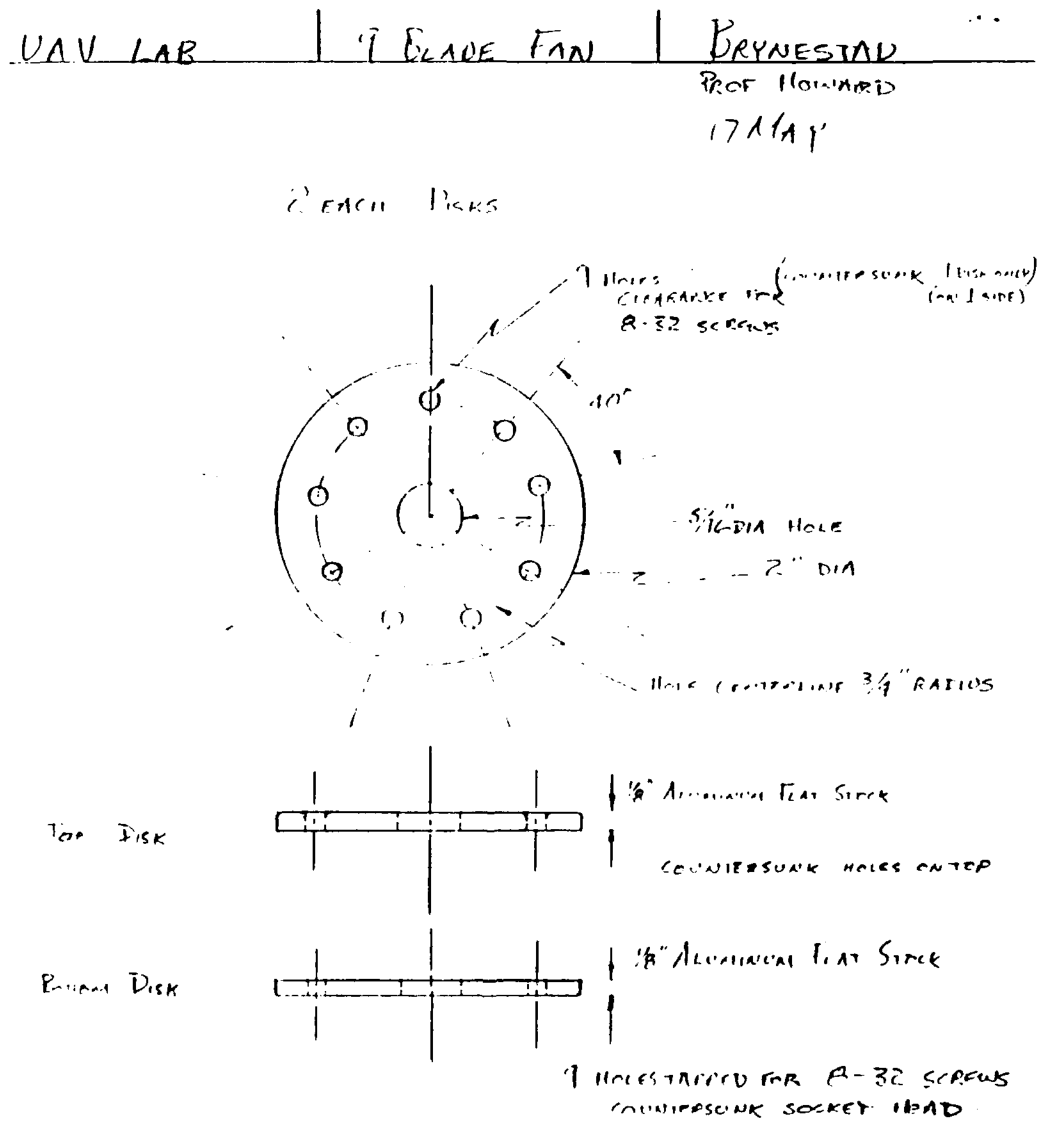
OTHER PIECES:

1. 3/8" DIA. ALUM. ROD, 6" LONG, FOR SLIDING FIT INTO YOKE.

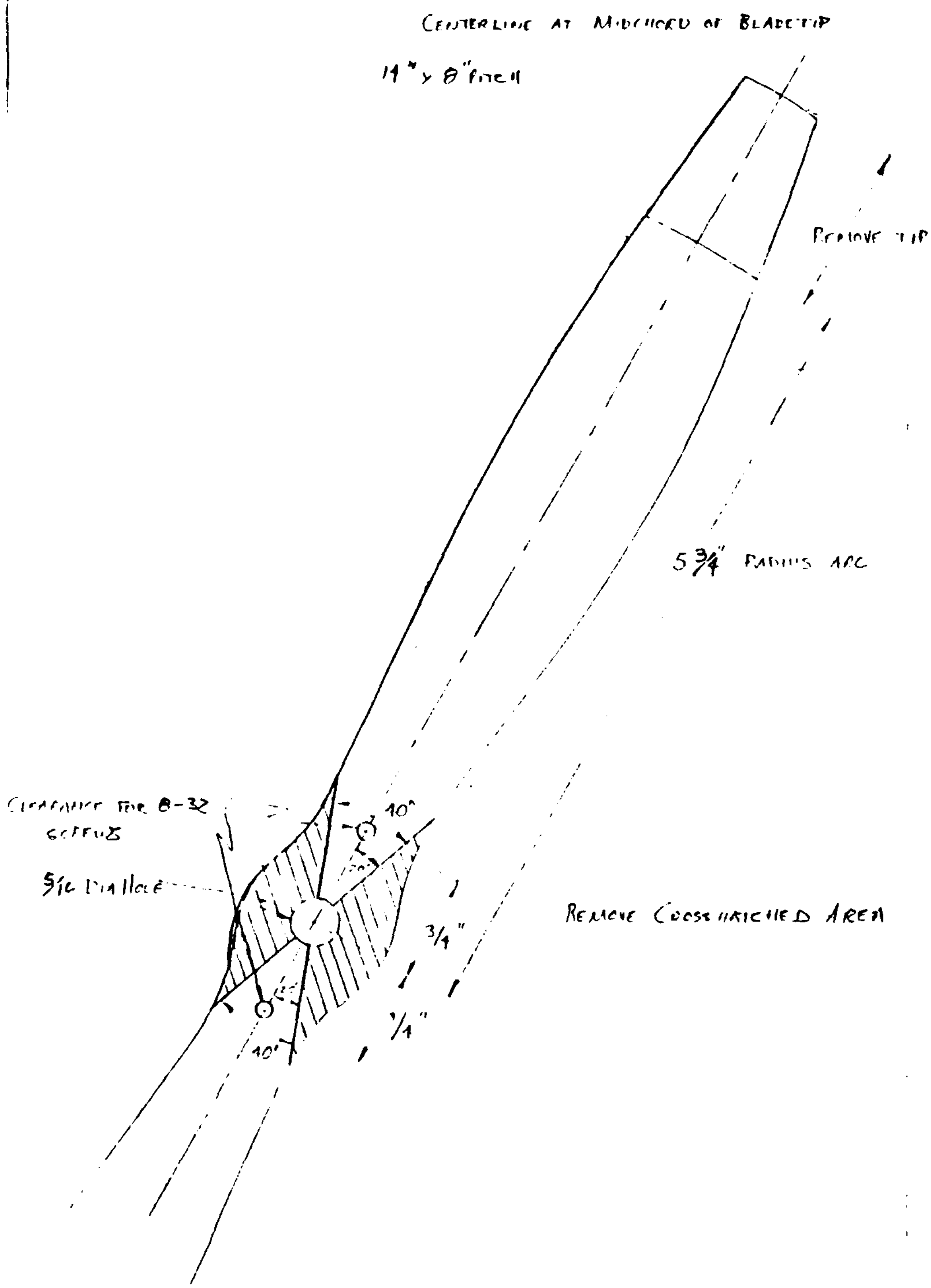
2. TWO 3/16" DIAM. STEEL RODS FOR SHOCK SUPPORTS, FOR TIGHT SLIDING FIT THRU HOLES IN YOKE (SEE ASSEMBLED DRAWING, 2.4" LONG, THREADED 1/4" BOTH ENDS (COARSE COMMON THREAD?)

APPENDIX B

NINE BLADED FAN DESIGN



UAV LAB	9 BLADE FAN	BRYNESTAD
		PROF HOWARD

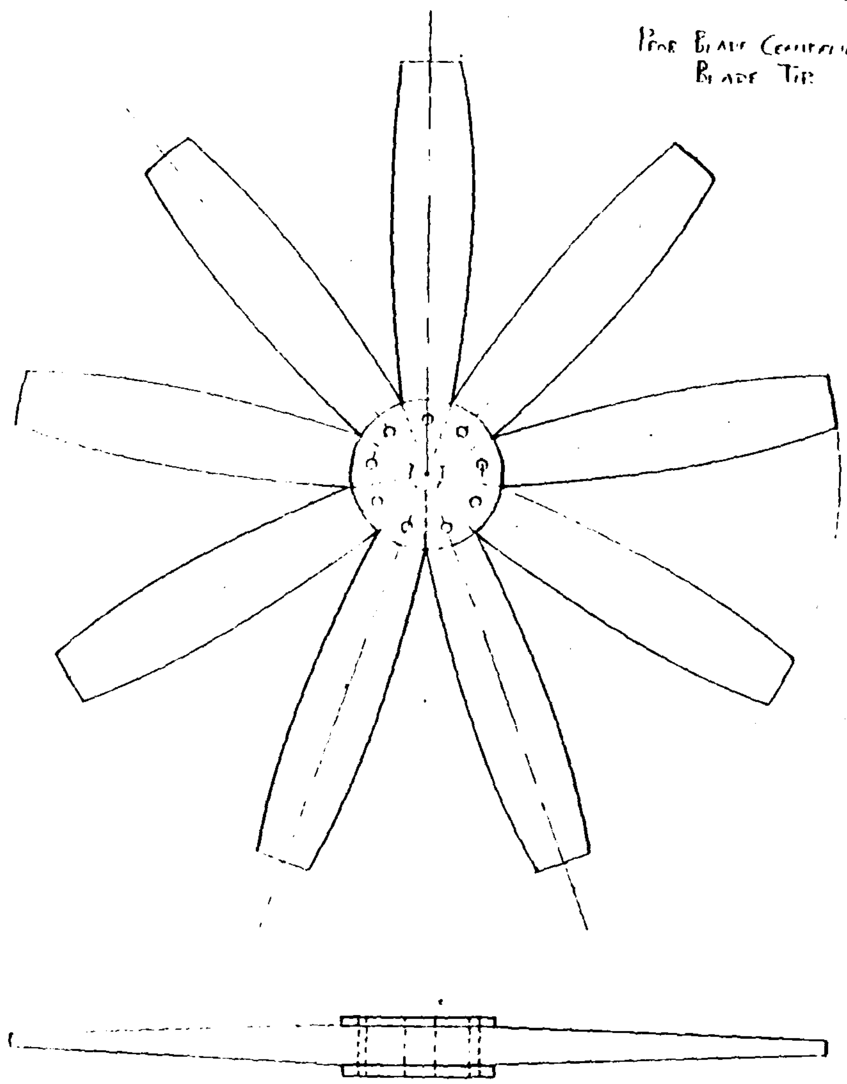


UAV LAB | 9 BLADE FAN | BRYNESTAD
PROF HOWARD

CUT 14" DIA PROPS
TO 5 1/4" RADIUS

PROPS TIPS 5 3/4" RADIUS CURVE
(NOT SQUARE)

PROP BLADE CENTERLINE PIERCES
BLADE TIP



1/2 SIZE

APPENDIX C

RADIO CONTROL MIX SETTINGS

The Futaba PCM 1024A radio transmitter has multiple functions available through many user selected menus to manipulate a radio controlled model aircraft. Among these functions is one to mix the control inputs. For example, a pilot might want to improve the roll rate of his aircraft by mixing flaps with ailerons, effectively giving his flapped aircraft full span ailerons. The Futaba transmitter can mix any of the eight channels to any other channel but is limited to only four of these mixes. It also has six preprogrammed mixes available that model pilots often use.

As discussed in Chapter III Section 7, each control vane of the ducted fan unit was assigned to a separate radio channel and mixed in the transmitter to move the ducted fan as desired. All four of the optional mixes and one of the preprogrammed mixes were required for manual control of the ducted fan. It was not possible to incorporate gyro stabilization into this control configuration. Table C.1 illustrates the mix settings viewed in the transmitter display to achieve the desired mixings.

Table C.1 RADIO CONTROL MIXING SETTINGS

User Selectable Mix:

1:PROG MIX

MX1	AIL→RUD	ON	-100%	-100%	1	OFF	+	0%
MX2	RUD→ELV	ON	-100%	-100%	1	OFF	+	0%
MX3	RUD→AIL	ON	+100%	+100%	1	OFF	+	0%
MX4	RUD→FLP	ON	+100%	+100%	1	OFF	+	0%

Preprogrammed Mix:

6:ELV→FLP
UP+100%
DN+100%
FLP TRM 30

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